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Comparison of three miniplate systems in experimentally induced ulnar and radial fractures in pigeons *(Columba livia)*

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1 Summary

Although bone plates have advantages over other fixation methods for certain indications, they are still uncommonly used in avian fracture repair. One reason are the thin cortices of avian bones. They lead to a reduced screw holding power. Another reason was that until now there was no evaluated plating system appropriate and available for the use of fracture repair in smaller birds. Therefore a study with three different miniplate systems was carried out. Three groups (A, B and C) of six pigeons (*Columba livia*) each were used. The left ulna and radius of the pigeons were transected and the ulna was repaired with a bone plate. Three plate systems were used: in group A, a 1.3 adaption plate; in group B the same plate with washers to achieve a limited contact system; in group C a maxillofacial miniplate. Healing was evaluated with radiographs after two and four weeks, a flight test was performed after 4 weeks, and a necropsy of the wing was carried out. Group A achieved the best flight results (100% good). In group B no effect of the limited contact concept was visible at necropsy and a high percentage of screws loosened which led to repair failure (33%). The maxillofacial miniplates of group C were too weak and bent (100%). In conclusion only the adaption plate 1.3 met the requirements for avian osteosynthesis. To adapt the system better to the properties of avian bone, further trials using smaller drill bits or screws with a smaller thread pitch should be carried out.

2 Zusammenfassung deutsch

Vergleich von drei Miniplattensystemen in experimentell induzierten Radius/Ulna-Frakturen bei Tauben *(Columba livia)*

Obwohl Platten zur Fixation von Frakturen erhebliche Vorteile gegenüber anderen Systemen aufweisen, werden sie in der Vogelchirurgie nur selten verwendet. Verantwortlich dafür sind einerseits die dünnen Kortizes der Vogelknochen, andererseits die limitierte Verfügbarkeit geeigneter Platten. In der vorliegenden Studie wurden in drei Gruppen (A, B und C) mit je sechs Tauben drei Plattensysteme untersucht. Der linke Radius und die linke Ulna wurden intraoperativ durchtrennt und die Fraktur anschliessend mit einer Miniplatte fixiert. In der Gruppe A wurde eine 1.3

Adaptationsplatte, in Gruppe B dieselbe Platte mit Unterlegscheiben und in Gruppe C eine Maxillofazialplatte verwendet. Die Heilung wurde mittels Röntgenbilder nach zwei und nach vier Wochen evaluiert. Zusätzlich wurde nach vier Wochen ein Flugtest durchgeführt, die Tiere anschliessend euthanasiert und der Flügel seziert. Gruppe A erreichte die besten Flugergebnisse (100% gut). In Gruppe B konnte kein Effekt des „limitierten Kontakt Konzepts“ festgestellt werden und in 33% ist die Fraktur nicht abgeheilt aufgrund gelöster Schrauben. Die Maxillofazialplatten der Gruppe C waren zu weich und haben sich verbogen (100%).
Fazit: Nur die 1.3 Adaptionsplatte scheint zur Osteosynthese bei Vögeln geeignet. Um das System besser an die Eigenschaften von Vogelknochen anzupassen, könnten in zukünftigen Studien kleinere Bohrer oder Schrauben mit einer geringeren Gewindesteigung eingesetzt werden.

3 Introduction

In human and small animal surgery bone plates are frequently used in osteosynthesis. Although for certain indications bone plates have clear advantages over other fixation methods, they are only rarely used in avian surgery. The main cause appears to be the lack of suitable plates in the small sizes required for avian fracture repair (Bennett and Kuzma 1992). Another reason is the belief that avian bone is more susceptible to comminuted fractures than mammalian bone (Bennett and Kuzma 1992). Until now only few published studies on the use of bone plates in avian surgery exist. The purpose of the present study was therefore to evaluate three different miniplate systems for their practicability for avian surgery. The experimental design was analogue to the study of Christen et al. (2005). Additionally a literature review on the properties of avian bone was performed to identify the differences to mammalian bone and their implications for avian osteosynthesis.

4 Literature

4.1 Pigeons *(Columba livia)*

The feral pigeon or street pigeon *(Columba livia)* belongs to the family of *Columbidae*. They originate from the rock pigeon *(Columba livia livia)* and domesticated pigeons that originally were also bred from rock pigeons. Pigeons are good flyers with a remarkable sense of direction. Because of their exceptional ability to adapt, feral pigeons are common in almost all cities around the world. While rock pigeons typically ingest grains, seeds, and sometimes slugs, feral pigeons have become omnivorous and eat waste as well as almost everything they are fed. The abundance of food supply in the cities has led to large populations of feral pigeons that make pest control necessary because of a variety of health and environmental problems necessary (Haag-Wackernagel 1998). Feral pigeons live in life-long monogamy. Under optimal circumstances, a breeding pair of feral pigeons is able to raise up to twelve fledged young per year. Pigeons are easy to handle as experimental animals. They have been used as experimental animals for example in endocrinological, biomedical, and behavioural research. Since feral pigeons may spend their entire life in the city, and therefore are exposed to the same pollutants as humans, they are also used as bioindicators of environmental pollution (Haag-Wackernagel 1998). Pigeons have also been used in several studies on fracture repair and bone healing (Bush et al. 1976b; Christen et al. 2005; MacCoy and Haschek 1988; Newton and Zeitlin 1977; Putney et al. 1983; Wan et al. 1994; Wander et al. 2000; West et al. 1996a; West et al. 1996b; Yamazoe et al. 1994).

4.2 Avian bones

There are several inconsistencies in the literature concerning the weight of avian bones, the reasons for bone pneumatisation, the chemical composition, the brittleness, and in particular the differences between avian and mammalian bones. As many clinical decisions concerning osteosynthesis are theoretically based on knowledge of bone constitution, the potential for avian osteosynthesis may well be misjudged due to a misconception regarding these issues.

4.2.1 **Weight of avian bones**

In textbooks of Hickman et al (1974), Welty (1975), Schwarze and Schröder (1985) and König et al. (2008) it is stated, that in animals of the same body weight, avian bones are lighter compared to mammalian bones as an adaptation to flight. However, measurements in an original research paper of Casinos and Cubo (2001) revealed that the long bones of birds (humerus, ulna and radius, femur as well as tibia and fibula) are heavier compared to the corresponding bones of rodents and insectivores of the same weight (100g). Prange et al. (1979) found as well in an original research paper that the skeletal mass of birds is not less than that of mammals in proportion to body weight.

4.2.2 **Pneumatisation of avian bones**

Schwarze and Schröder (1985) as well as König et al. (2008) note in textbooks, that pneumatisation leads to a reduction of weight and therefore to better flight abilities. They also state that pneumatisation is more developed in good flyers, e.g. pigeons, while in poorer flyers, e.g. chickens, most bones are filled with bone marrow. On the other hand, Cubo and Casinos (2000a) conclude in a original research paper that although pneumatisation of bones should contribute to a low density of the skeleton, there is no direct relationship between flight ability and bone pneumatisation. For example, gulls lack pneumatised long bones (Cubo and Casinos 2000a) but nevertheless are excellent flyers. In birds in general there is rather an internal redistribution of skeletal mass to the leg bones, instead of a reduction of skeletal mass (Prange et al. 1979). This contradictory information indicates, that the knowledge in this matter is not as profound as stated in the general anatomical literature of birds.

Pneumatisation of bones requires pneumatic foramina where an airsac extends into the hollow interior of the bone and connects the bone with the respiratory system (Casinos and Cubo 2001). Therefore, the penetration of a pneumatised bone also opens access to the respiratory system: in open avian fractures of a pneumatised bone, antibiotic and antimycotic treatment are necessary to avoid infection of the respiratory system (Lierz 2004).

4.2.3 **Chemical composition of avian bones and its consequences for mechanical properties**

With respect to the chemical composition of avian bones and its consequences there are also inconsistencies in the literature. Martin and Ritchie (1994) remark that the calcium (Ca) content in avian bones is high. Bush et al. (1976b), Schwarze and Schröder (1985) and Bennet (1992) state that avian bones have an increased brittleness because of their high Ca content and Schuster (1996) and Dunning (2002) even claim that avian bones have a higher Ca content *than mammalian bones* and are therefore more brittle. Nickel et al. (2004b) states that the calciumphosphate content of domestic mammals is 85% and the content of calciumcarbonate is 10%. The same calciumphosphate and calciumcarbonate levels are indicated for birds (Nickel et al. 2004a). However, empirical evidence for these assumptions is neither given nor referenced in these textbooks. In studies of Biltz and Pellegrino (1969) (Tab. 1) and Currey (1988) (Tab. 2), measured Ca levels were not higher in avian as compared to mammalian bone. However in these two studies only bones of non-flying birds (ground-dwellers and aquatic birds) were examined. Therefore this matter remains unresolved.

Tab. 1: Data of calcium (Ca) content of bones of different species in mg/g (dry matter and fat extracted) (Biltz and Pellegrino (1969)

Species	**n**	**Ca (mg/g)**
Fish	2	232.6
Turtle	6	245.0
Frog	4	246.9
Polar Bear	1	247.5
Man	15	256.9
Elephant	1	260.1
Monkey	3	261.4
Cat	1	266.0
Horse	3	264.4
Chicken	**4**	**263.1**
Dog	10	266.8
Goose	**2**	**269.4**
Cow	5	275.9
Guinea Pig	2	270.1
Rabbit	2	282.1
Rat	12	288.1

Tab. 2: Data of calcium (Ca) content of different bones of different species in mg/g (dried at 60°-70° for 30min and fat extracted) (Currey 1988). The localisation of the bone was specified as well as the number of animals and the standard deviation (S.D.). The state of the bone indicates if it had been deep frozen (F) or dried out at some stage (D)

Species	**Bone**	**n**	**Ca content (mg/g)**	**S.D.**	**State of bone**
Roe deer	antler	1	174.3		D
Red deer	antler	8	208.3	19.1	D
Reindeer	antler	4	225.3	11.59	D
Galapagos tortoise	femur, fibula	5	226.1	15.31	F
Muntjac deer	antler	1	226.8		D
Atlantic whale	posterior rib	4	241.1	11.19	F
Donkey	radius	4	247.6	8.61	F
Crocodile	frontal	2	250.7	10.27	D
Sheep	metacarpus	5	251.3	7.25	F
Atlantic whale	anterior rib	4	251.8	12.99	F
Alligator	femur	6	252.9	13.15	F
Blackfooted penguin	**radius, humerus**	**2**	**262.1**	**17.33**	**F**
Horse	femur	4	267.8	8.83	F
Grey seal	femur, humerus	4	270	6.18	F
King penguin	**humerus**	**2**	**270.1**	**1.68**	**F**
Fallow deer	tibia	4	274.1	8.25	F
Wallaby	femur, tibia	4	274.1	6.02	F
Cow	femur, tibia	7	296.8	14.72	F
Fin whale	bulla yellow part	3	309.1	15.53	F
Fin whale	bulla white part	4	311.4	10.33	F

Cubo and Casinos (2000b) measured in dried but not fat extracted avian bones of 46 different species a mean Ca content of 22.86% (228.6 mg/g). Note that due to the lack of fat extraction, this value must not be compared to the data in Table 1 and 2.

Bone mineral density (BMD) and bone mineral content (BMC) were measured with peripheral quantitative computer tomography (pQCT) in several species, including birds and - as a mammal with flight ability - also mustached bats *(Pteronotus parnellii rubiginosus).* There were major inconsistencies in the measuring units between the

different publications. For this reason, measuring units were adapted in agreement with one author (Liesegang). Bone mineral density and bone mineral content do not seem to be higher in birds compared to mammals (Tab. 3). However there are large differences in bone mineral density (BMD) and bone mineral content (BMC) depending on the site, age (Schneider et al. 2004), sex, and diet (Liesegang et al. 2008).
Another method to determine BMD and BMC is dual-energy X-ray absorptiometry (DEXA). For this method the required radiation dose is 30 times lower than with pQCT and it is less expensive (Grier et al. 1996). The measurements with DEXA are highly dependent on the measured region and the positioning of the animals (Grier et al. 1996). Additionally age, sex, and diet most likely have similar influences on BMD and BMC as assessed with the pQCT method. In a comparison of literature data on DEXA measurements of BMD and BMC of different mammals and birds, BMD and BMC do not seem to be higher in birds than in mammals (Tab. 4).

Currey (1984) indicates that differences in mineralisation clearly have a profound effect on the Young's modulus (stiffness). Very high values of mineralization produce high values of Young's modulus (stiffness) but a low fracture toughness. On the basis of the available literature (Tab. 1 and 2) it is not possible to claim that avian bones have a higher mineral or Ca content than mammalian bones and are therefore more brittle.

Tab. 3: Literature data on bone mineral density (BMD) and bone mineral content (BMC) determined with peripheral quantitative computed tomography (pQCT) in different species including birds and mammals, sorted in descending order by BMD. Measuring units adapted in agreement with A. Liesegang (pers. comm.)

Species	Bone	BMD (mg/cm^3)	BMC (mg/mm)	Author
Sheep	metatarsus	740 - 910	1.75 - 1.99	(Liesegang et al. 2006b)
Goat	metatarsus	750 -855	1.45 – 1.79	(Liesegang et al. 2006b)
Dog	femur	600 – 700		(Schneider et al. 2004)
Pig	phalanx and tibia	410 - 510	0.75 – 3.20	(Liesegang et al. 2002)
Mustached bats *(Pteronotus parnellii rubiginosus)*	radius	430		(Liesegang et al. 2006a)
Budgerigar *(Melopsittacus undulatus)*	tibiotarsus	males 362 - 373 females 510 - 545	males 0.98 – 1.04 females 1.7- 1.95	(Liesegang et al. 2008; Zulauf-Fischer et al. 2006)(Zulauf-Fischer et al. 2006; Liesegang et al. 2008)
Feral pigeon *(Columba livia)*	tibiotarsus	300		(Liesegang et al. 2008)
Chinese mountain goat	humerus and femur	90 -100		(Siu et al. 2003)
Mouse	femur		1.5 ± 0.1	(Uusitalo et al. 2001)

Tab. 4: Literature data on bone mineral density (BMD) and bone mineral content (BMC) determined with dual-energy X-ray absorptiometry (DEXA) in different species including birds and mammals, sorted in descending order by BMD.

Species	Bone	BMD (g/cm^2)	BMC (g)	Author
Horse	metacarpus	0.29 – 4.80		(McClure et al. 2001)
Sheep	femur	0.94	52.3	(Deloffre et al. 1995)
Dog	femur	ca. 0.73 – 0.79		(Schneider et al. 2004)
Chinese mountain goat	femur	0.67		(Siu et al. 2003)
Pig	metacarpus	0.55 – 0.58	0.42 – 0.53	(Nielsen et al. 2004)
Wild turkey *(Meleagris gallopavo)*	femur	0.54	11.5	(Dirrigl et al. 2004)
Single comb white leghorn hens	femur	0.18 - 0.27	1.57 – 2.55	(Kim et al. 2006)
Ruffed grouse *(Bonasa umbellus)*	femur	0.15	0.55	(Dirrigl et al. 2004)

4.2.4 Cortical thickness of avian bone and its consequences for mechanical properties

While in mammals long-bones are mainly exposed to bending and compression, the avian wing-bones are highly exposed to torsion (de Margerie 2002; Garcia and da Silva 2006). Currey and Alexander (1985) examined the ratio of the radius to the cortex thickness in more than 240 long bones from 70 species. Terrestrial mammals, flying and flightless birds as well as bats and Pterosaurs were evaluated. Birds, Pterosaurs, and bats have thinner-walled forelimb bones compared to terrestrial mammals (Currey and Alexander 1985; Swartz et al. 1992). Swartz et al. (1992) postulated that the hollow geometry of bird and Pterosaur bones is an adaption to minimize torsional stresses rather than a weight reduction. In pneumatised bones, cortical thickness and bending strength are even lower than in marrow-filled bones (Casinos and Cubo 2001). The thin walled cortices of birds might cause problems in osteosynthesis because the holding strength of bone screws increases with the number of threads per cortex (Seebeck et al. 2000). This might explain why Levitt (1989) attributes avian bone a poor screw-holding power. Additionally, thin-walled bones are weaker under localized impact (Currey and Alexander 1985). The thin cortices represent a *physical* reason for the alleged increased brittleness attributed to avian bones, whereas the contribution of the *chemical* composition remains unclear (see chapter 3.2.3).

4.2.5 Bone morphology and medullary bone

Compared to mammalian bone, mature cortical bone of pigeon humeri contains relatively few osteons. Osteons are columns of bone that are aligned parallel to the long axis of the diaphysis. In birds, cortical bone is arranged in a circumferential lamellar pattern instead (Dunning 2002; West et al. 1996b). It has been speculated that this might increase the brittleness of avian bone; however, it should be noted that this alleged “increased brittleness” has not been quantified itself, so that not only the explanation, but also the concept that is explained by it remain speculative.
Under the influence of oestrogens and testosterone, female birds form medullary bone during the ten days prior to egg laying as a calcium store (Johnson 2000; Zulauf-Fischer et al. 2006). Medullary bone is more calcified than cortical bone, and in contrast to cortical bone, the apatite crystals are more randomly arranged rather than being aligned to the matrix (Dacke et al. 1993).

Bush et al. (1976b) states that the dynamics of bone repair in avian species appears to be little affected by the absence of bone marrow in pneumatised bone. But compared to mammals, comminuted fractures occur very often (Bush et al. 1976a). Therefore the prognosis for return to function after repair of avian fractures is often poor (Wander et al. 2000). However well aligned, stable fractures in birds seem to heal faster than mammalian fractures. After two to three weeks a simple closed fracture is often clinically stable (Bennett 1997). But until radiographically visible callus can be detected, three to six weeks are necessary. The radiographic union often lags behind the clinical union (Bennett 1997).

In a study of Bush et al. (1976b) either humerus, ulna or both radius and ulna were manually fractured in pigeons and not fixated. Signs of a bridging bony callus were observed radiographically at approximately two weeks in well-aligned ulnar fractures. However this callus could be more clearly visualized after three weeks. In a study of Wander et al. (2000), induced humeral fractures in pigeons were fixated with intramedullary xenograft bone pins. In that study palpatory stability was achieved after three weeks and the structural strength was equivalent to the contralateral side six weeks after fracture fixation.

4.3 Surgical anatomy and physiology of the avian antebrachium

4.3.1 Radius and ulna

The thoracic limb is provided with a mechanism that provides simultaneous flexion or extension of the elbow and the carpus. During this process, the ulna slides along the radius (Orosz 2002; Orosz et al. 1992). In birds the radius is the smaller bone (Orosz 2002), while in mammals the ulna has undergone more reduction than the radius (Sears et al. 2007). The avian ulna is located caudally to the radius (Olsen et al. 2000) and is more curved than the radius (Pennycuick 1967). Neither radius nor ulna are pneumatised. They articulate with each other at the ends, but are not fused (Pennycuick 1967). The degree of the curvature of radius and ulna depends on the manner of flight. The radius and ulna of birds with flapping flight (e.g. *Columbiformes*) is more curved, while birds with a gliding flight have relatively straight bones (Cubo et al. 1999; Orosz 2002).

4.3.2 **Feathers**

The secondary remiges insert directly into the caudal surface and the periost of the ulna (Martin and Ritchie 1994; Olsen et al. 2000). Cut feathers are only replaced during molting and many birds molt only once a year. Plucking or cutting flight feathers needs to be avoided. If damage to the follicle occurs, regrowing feathers may be malformed. Therefore a skin incision for osteosynthetic surgery has to be made cranially to the secondary remiges (Bennett and Kuzma 1992; MacCoy 1996; Orosz et al. 1992). For aseptic preparation of the surgical site, the secondary remiges must not be plugged but can only be covered with a sterile drape.

4.4 Most common fractures

Trah and Wrieg (1984) analyzed the occurrence and localisation of fractures in different kinds of birds. They noticed a different relation of wing and leg fractures between wild birds and pet birds. In the examined wild birds 70% of the fractures were wing fractures while in pet birds leg fractures occurred more often. In racing pigeons as well as feral and some fancy pigeons that were presented at a clinic in Birmingham, wing fractures were two and a half times more common than leg fractures. Fractures of the radius and ulna occurred in 10.6% of all wing problems, while fracture of the radius only occurred in 5.2% and fracture of only the ulna in 1.3% of the cases (McCartney 1994).

4.5 Treatment methods of radius/ulna fractures

Wild birds require nearly complete return to function prior to re-release into the wild, while pet birds or other caged birds may live with a compromised flight ability (Bennett and Kuzma 1992). The success of fracture treatment depends on the type of fracture, the condition of the fracture and the surrounding soft tissue, the kind of fractured bone and the method of fracture fixation (Howard and Redig 1993). The goals of fracture repair in avian species are the same as in mammals: accurate alignment and rigid stabilisation of the fracture fragments to allow minimal callus formation and as little soft tissue damage as possible (Bennett and Kuzma 1992; Howard and Redig 1994; MacCoy 1991). Exuberant callus formation or synostosis due to fracture healing may inhibit the sliding mechanism between radius and ulna and prevent full flight ability (Christen et al. 2005; Howard and Redig 1994; Kuzma and Hunter 1991). In case of synostosis Howard and Redig (1994) recommend removing of the osseous bridge between the two bones. To prevent the formation of a new synostosis a fat graft can be placed between the bones at the location of the former synostosis (Howard and Redig 1994). Furthermore birds quickly develop joint ankyloses if joints are immobilised over extended periods; therefore, long healing periods have to be avoided (Conzemius and Kopf 1991).

4.5.1 **Cage rest**

Fractures of the radius alone can be treated with cage rest with acceptable outcome, particularly in young growing birds (Hatt 2008). In this case the larger ulna serves as a splint for the smaller radius (Martin and Ritchie 1994). This type of fracture management should only be applied to small birds with minimally displaced fractures, where return to full flight ability is not absolutely necessary (Bennett and Kuzma 1992). However, Redig and Cruz (2008) recommend cage rest without fixation only for very proximal radial fractures. Disadvantages of this method are prolonged healing time with excessive callus formation, sometimes severe malalignment and probably reduced flight ability. Additionally, excitable birds with unstable fractures may traumatize themselves (Bennett and Kuzma 1992).

4.5.2 **External coaptation**

External coaptation implies fracture fixation with bandages, splints, and slings (Orosz 2002). Figure-of-8 bandages are best suited for fractures of the antebrachium (Bennett and Kuzma 1992; MacCoy 1996). Indications for fracture repair with a bandage are birds that are too small for surgical fracture repair, birds with a too high anaesthetic risk, minimally displaced fractures, and highly comminuted fractures (Bennett and Kuzma 1992). Pathologic fractures (metabolic bone disease) and fractures in birds in which full return to function is not required (Orosz 2002; Redig and Cruz 2008) can also be stabilized with a figure-of-8 bandage.

Advantages of external coaptation are its low costs, its simple application and short anaesthesia duration (Bennett and Kuzma 1992). Furthermore the risk for possible infections is reduced without implants, there is minimal disruption to the fracture site, the blood supply is not compromised and there are no implants interfering with growth in young animals (Weinstein and Ralphs 2004).

The location of the fracture is important considering external coaptation. If the fracture is located close to a joint, the fracture ends more likely damage articular or periarticular structures, therefore this type of fracture is less suited for external coaptation (MacCoy 1992).

Midshaft radius and ulna fractures may be supported with a figure-of-8 bandage in birds weighing less than 100g (MacCoy 1992). If the radius is intact and the ulnar fracture stable figure-of-8 bandages may also be sufficient (Redig and Cruz 2008). If only the ulna is fractured transversally and well aligned, bandaging with a figure-of-8 bandage is acceptable. But after three weeks of immobilisation contraction of the patagium may occur (Redig 2001). Fractures of the distal two-thirds may be treated with a figure-of-8-bandage, if there is no severe displacement of the fragments (Howard and Redig 1994).

Complications of external coaptation are slipping of the bandage (Bennett and Kuzma 1992), dermatitis, swelling of the surrounding soft tissue (Weinstein and Ralphs 2004), nonunion, imperfect alignment that requires longer healing time (Orosz 2002), joint ankylosis, tendon contraction, and excessive callus formation (Bennett and Kuzma 1992). All these conditions may lead to impaired flight ability.

4.5.3 Intramedullary pins (IM pins)

The application of intramedullary (IM) pins is a relatively simple and inexpensive technique (Bennett and Kuzma 1992). Intramedullary pins provide alignment of the fracture fragments and neutralize bending forces but they do not provide for stability against shear forces and rotation (Bennett and Kuzma 1992; Meiners 2007; Newton and Zeitlin 1977). Smooth pins as well as positive or negative threaded pins are used. They may be placed with a hand chuck or manually (Hatt 2008). The location and method of the placement of IM pins is important to prevent the joints from damage. The radius can be pinned retrogradely with the pin exiting at the distal end without damaging the carpal joint. In contrast the ulna must be repaired by normograde placement of the IM pin just distal to the point of attachment of the triceps tendon.

4.5.4 **External fixators**

External skeletal fixators (ESF) provide adaptation and stabilize fractures against rotation, bending, and shear forces. Surgical damage to the blood supply is minimal and the removal of implants is easy (Hatt 2008). Indications for ESF are comminuted fractures, open and contaminated fractures, meta- and epiphyseal fractures as well as corrective osteotomies (Meiners 2007). In avian surgery ESF are often used in cases where complete restitution of function has to be achieved. Most frequently uniplanar type 1 splints and uniplanar type 2 splints as well as tie-in ESF (a combination of external fixation and intramedullary pin) are applied (Hatt 2008). For ulnar fractures a type 1 ESF or a tie-in fixator may be used (Redig and Cruz 2008). Kirschner-Ehmer fixators can be used, however their main disadvantage is their weight, cost and size of clamps (Bennett and Kuzma 1992). The FESSA (Fixateur Externe du Service de Santé des Armées) tubular external fixator is lightweight and the clamps are replaced by small screws. Tubes filled with polymethylmethacrylate (PMMA) as connecting bars can be used as an alternative connecting bar. They are also lightweight, adapted to the form of the bone and in less expensive (Hatt 2008). Generally ESF are well tolerated (Lierz 2004). A common complication is drainage around a fixation pin (Hatt 2008). External fixators are frequently used because they require minimal soft tissue manipulation and short surgical time. However, they often do not provide exact adaptation of the fracture fragments, which is essential in repairing fractures involving the joint.

4.6 Bone plates used in avian species

In human and veterinary surgery, bone plates are widely used. Their advantages over other methods of fracture fixation are rotational stability, rigid internal stability, and avoidance of joint involvement. These factors lead to an earlier return to function compared to other methods (Bennett and Kuzma 1992; Howard 1990; Johnson 2007). The rigid fixation allows early pain-free mobility and prevents fracture disease. With bone plates healing with little or no external callus formation is possible (Coughlan and Miller 1998). In addition, because the plates are applied internally, they are well tolerated (Martin and Ritchie 1994) and destruction of the fixation with the beak or getting caught in the fixation is unlikely (Hatt 2008). Bone plates enable excellent reduction and alignment of the fractures; therefore, when dealing with avian patients, restoring full function is possible in many birds by using plates (Martin and

Ritchie 1994). In small animals bone plates are recommended in fractures, where anatomical reconstruction and minimal callus formation are required, e.g. articular fractures, in fractures that require compression e.g. non-union fractures, to buttress non-reconstructable fractures and for arthrodesis (Coughlan and Miller 1998).

Disadvantages of fracture fixation with bone plates compared to other methods are the expensive equipment, the technically difficult surgery that requires a trained surgeon, prolonged anesthetic and surgical times (Bennett and Kuzma 1992) and the wide exposure of bone with concurrent soft tissue damage that is required (Coughlan and Miller 1998). Another disadvantage of bone plates is that removal of the plate is recommended after the fracture has healed. The reasons are, that in mammals, painful cold transduction as well as weakening of the bone at the location of the plate have been reported. Therefore, a second surgery is recommended – especially in wild birds prior to release (Bennett and Kuzma 1992).

Other reasons why bone plates are not commonly accepted in avian surgery are the thin and brittle cortices of avian bones, that are believed to be prone to iatrogenic fractures (Bennett and Kuzma 1992; Kuzma and Hunter 1991). Additionally, there is the common belief that the thin cortices of avian bones will not hold bone screws well (Bennett and Kuzma 1992; Degernes et al. 1998; Levitt 1989; Withrow 1982). However, in a study of Howard (1990) semitubular plates were applied to repair tibiotarsal fractures in a sandhill crane *(Grus canadensis)* and a red-tailed hawk *(Buteo jamaicensis)*. The plates bent and were severely deformed but in both cases all but one screw remained secured. Therefore, this author doubted that avian bone is unable to hold bone screws well enough.

Bone plates should be applied to the tension surface of bones to absorb the tensile stress that could separate a fracture. In general the compression occurs on the concave surface of the bone and the tension on the convex surface of the bone (Johnson 2007). Because in avian bones the tension surfaces are not yet defined (Bennett and Kuzma 1992), osteosynthesis in birds is considered even more difficult. Nevertheless bone plates have already successfully been used in several avian species (Bush et al. 1976a; Christen et al. 2005; Davidson et al. 2005; Hatt et al. 2001; Howard 1990; Kuzma and Hunter 1989; Kuzma and Hunter 1991). Mainly metal veterinary cuttable plates as well as acrylic plates (Martin and Ritchie 1994) are easily available in sizes that are useful in larger birds.

4.6.1 **Adaption plate 1.3**

The 1.3 Adaption plates of the Modular Hand System (Fig. 1) were originally intended for reconstructive procedures of selective trauma of the distal middle phalanges in human medicine (Synthes GmbH, Oberdorf, Switzerland, "manufacturer information"). The plates have a low profile to reduce soft tissue irritation and are precontoured for a better anatomic fit. The 1.3 adaption plate is 48 mm long with 12 holes, has a pre-bent profile, is 0.7 mm thick, 3.4 mm wide, and the hole spacing is 4.0 mm. The modular Hand System is available in stainless steel as well as in titanium. The 1.3 adaption plate is the smallest plate of this system. Screws only are available in a diameter of 1 mm. Larger plates that function with screws of 1.5, 2.0 and 2.4 mm diameter as well as different plate shapes (e.g. H, T and Y shaped) are available. For the sizes 2.0 and 2.4, even plates with locking mechanism (limited contact dynamic compression plate; LC-DCP®) are available. The 1.3 screws are self-tapping and have a low-profile head that reduces soft tissue trauma. They have a 1.3 mm thread diameter, 0.9 mm core diameter, a thread pitch of 0.5 mm, are 6 mm long and have a head diameter of 2.4 mm.
To the author's knowledge there are no publications on the use of 1.3 adaption plates in veterinary medicine. But Martin and Ritchie (1994) recommended small finger plates designed for human medicine for avian surgeries.

Fig. 1: Adaption plate Synthes GmbH, Oberdorf, Switzerland)

4.6.2 **Adaption plate 1.3 with washers**

To reduce compression of the periostum and vascular damage to the plated bone segment, plates with limited or pointed contact to the bone were designed (Jörger 1987; Perren et al. 1990; Tepic et al. 1992). These plates have a grooved or pointed plate undersurface which improves the blood supply of the plated bone segments.

Another development in plate osteosynthesis were the so-called internal fixators or plates with a locking mechanism (Schütz and Südkamp 2003). These plates reduce the negative effects of compression forces on the periostum by providing angular stability by the locking mechanism of the screw in the implant. Internal fixators and plates with limited contact to the bone are increasingly used in veterinary medicine (Venzin and Montavon 2007; Voss et al. 2004; Voss et al. 2006). However, the smallest plates commercially available for the author were too large to fixate ulnar fractures of pigeons.
Another system that provides locking screws to a bone plate are the Schuhli nuts (Schuhli: Swiss German for little shoe) (El-Sayed et al. 2001; Kolodziej et al. 1998). It consists of a cortex screw, a washer, the bone plate and a Schuhli nut (Fig. 2). This device locks a cortical screw to a bone plate at a fixed 90° angle. Additionally the nut elevates the plate above the cortical surfaces and minimizes therefore the contact between the plate and the bone (Kolodziej et al. 1998).

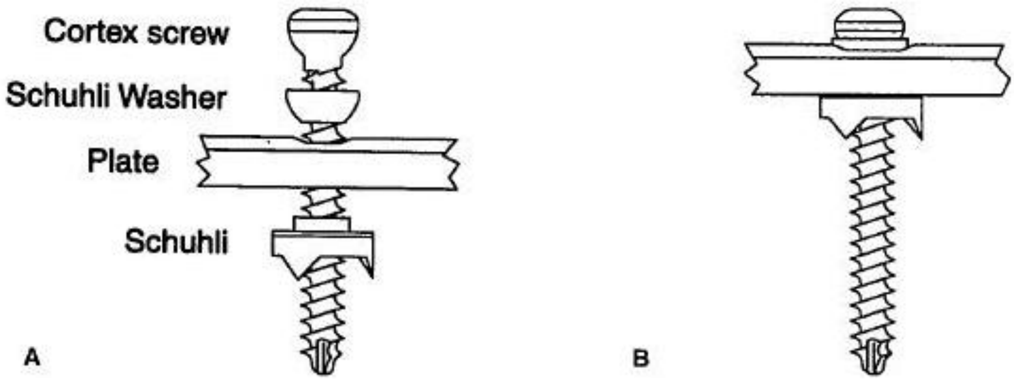

Fig. 2: a) Diagram with the compontents of the Schuhli system (Kolodziej et al. 1998): cortex screw, Schuhli washer, plate and Schuhli. b) Final appearance of the Schuhli system.

To find a plating system that provided limited contact and is appropriate for the size of the pigeons, an alternative solution similar to the Schuhli system was created with washers that were placed underneath the plate (Fig. 3). These washers were made from cut plate holes and therefore consisted of the same material as the plate. In contrast to the Schuhli system, a locking mechanism is not achieved with the washers because they do not have a thread.

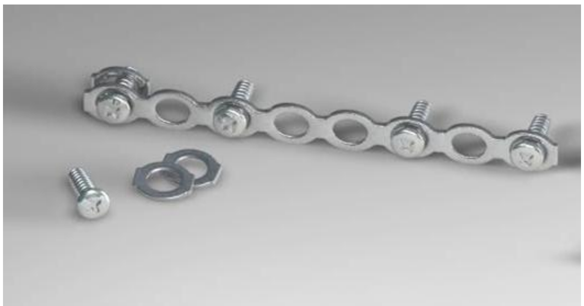

Fig. 3: 1.3 Adaption plate Synthes GmbH, Oberdorf, Switzerland) with two prepared washers and one washer placed on the screw at the left end of the plate.

4.6.3 **Maxillofacial miniplate, Compact 1.0**

The Maxillofacial 1.0 system consists of various preshaped titanium adaption plates and meshes, and is originally intended for craniofacial surgey and orthognatic surgery of the midface in human medicine (Synthes GmbH, Oberdorf, Switzerland, “manufacturer information”). The maxillofacial miniplate, Compact 1.0 is 34 holes long and 0.7 mm thick (Fig. 4). It is cuttable and consists of pure titanium. The screws are self-tapping, have a core diameter of 0.7 mm and a thread diameter of 1.0 mm. In cases of too large screw holes, additional emergency screws with a larger diameter are available (core diameter 0.9 mm, thread diameter 1.2 mm). The plating system is also available in larger sizes (1.3, 1.5, 2.0), but only in titanium (Synthes GmbH, Oberdorf, Switzerland, “manufacturer information”). The screws are self-tapping, which has the advantage that time consuming predrilling and tapping of screw holes is not necessary (Hatt et al. 2001).

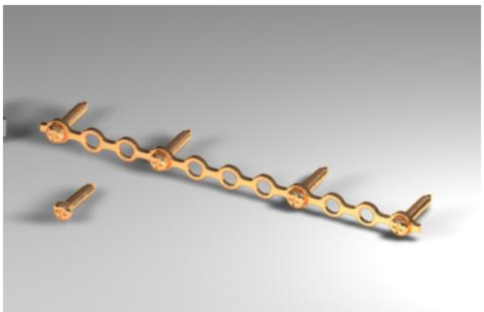

Fig. 4: Sample of a maxillofacial miniplate, Compact 1.0 Synthes GmbH, Oberdorf, Switzerland)

The low profile of Maxillofacial miniplates (0.7 mm thickness) allows wound closure with minimal tension compared to other plates (von Werthern and Bernasconi 2000) and also at locations with only little soft tissue covering (Hatt et al. 2001). Von

Werthern and Bernasconi (2000) state that the bone thickness should be at least twice the thread pitch distance of the screw to create adequate compression. The 1 mm screws of the maxillofacial plate, compact 1.0 have a thread pitch of only 0.25 mm which allows compression in even 0.5 mm thick cortices.

The Maxillofacial miniplates, Compact 1.0 are the smallest implants of that system and therefore useful for miniature fractures. In cats and toy breed dogs these plates, or the corresponding screws only, have been used for several indications: mandible fractures, metatarsal fractures, a phalangeal fracture and an avulsed collateral ligament of the metatarsal-phalangeal joint (Lewis et al. 2008; von Werthern and Bernasconi 2000). Maxillofacial miniplates, Compact 1.0 were also already used in avian surgery. A distal tibiotarsal fracture in an African grey parrot *(Psittacus erithacus)* was double-plated with two maxillofacial miniplates which resulted in a very satisfying outcome (Hatt et al. 2001). Christen et al. (2005) evaluated a the use of maxillofacial miniplates, Compact 1.0 for stabilization of the ulna in experimentally induced ulnar and radial fractures in pigeons. In six pigeons, the ulna and radius were transected to produce a diaphyseal fracture. Subsequently the ulna was stabilized with a 6-hole maxillofacial miniplate. However, the plate was too weak to adequately stabilize the fracture. Plate distortion, bending or in one case even plate failure occurred.

Larger models of this system (maxillofacial miniplate 2.0) were used in small animal medicine, e.g. to treat mandibular defects dogs and cats (Boudrieau and Kudisch 1996; Lewis et al. 2008).

4.7 Aim of the study

Although plate fixation has advantages over other fixation methods for certain indications, it is very rarely used in avian surgery, especially in birds with a bodyweight below 1 kg. So far none of the tested implants have proven entirely satisfactory. The aim of the study was therefore to evaluate miniplates, intended for human hand and face surgery, for their applicability in birds. With bone plates a better adaptation of the fracture ends is achieved, which is thought to result in improved healing. The evaluated features were the technical feasibility, stability, healing process, and flight ability. The ultimate goal would be to provide the avian clinician with future alternatives to conventional methods of fracture fixation and to use progress made in human and small animal surgery also in avian veterinary practice.

5 Animals, Materials and Methods

5.1 General

Three groups A, B, and C of six pigeons (*Columba livia*) each and two pigeons for a preliminary trial were used in this study. The left ulna and radius of the pigeons were transversely transected with an oscillating bone saw and the ulna was fixated with a bone plate. Three different plate systems were used: group A stainless steel 1.3 adaption plate (Synthes GmbH, Oberdorf, Switzerland), group B again the stainless steel 1.3 adaption plate, but additionally washers were placed between the plate and the bone and in group C a titanium maxillofacial miniplate, Compact 1.0 (Synthes GmbH, Oberdorf, Switzerland).

5.2 Animals

For this study pigeons of two origins served as experimental animals. The reason for using pigeons as experimental animals is their size that is similar to psittacine birds or raptors - species most likely to benefit from osteosynthesis. Additionally pigeons are birds with excellent flight ability in contrast to more ground dwelling birds like chicken and quails. The preliminary trial was carried out with two feral pigeons that were caught as part of the population control program of the city of Zurich. For the actual trial 18 pigeons from a local breeder were used. The 18 pigeons were divided into three groups of six pigeons each (A, B, and C). All animal procedures were approved by the cantonal Animal Care and Use Committee (license number 129/2008).

Before the beginning of the study, all animals were clinically examined and individually marked with coloured plastic rings. The body mass ranged from 277-354g. The sex of the pigeons was not determined. Blood samples were taken from all pigeons and only pigeons with hematologic values within normal limits (Carpenter 2005) were used for this study. The pigeons from the breeder were tested negative for *Chlamydophila psittaci* with an antigen ELISA. But one of the feral pigeons from the preliminary study was tested positive for *Chlamydophila psittaci*, therefore these two pigeons were treated with doxycyclin hyclate (Doxycyclini hyclas, 200mg/l drinking water for 4 weeks, Streuli Pharma AG, Uznach, Switzerland). Pooled fecal samples were examined for *Salmonella spp*. and intestinal parasites. The parasitological examination of the feral pigeons revealed *Eimeria* spp. and *Ascaridia/Heterakis*. Therefore, the feral pigeons were treated with toltrazuril (Baycox 5%®, 75mg/l drinking water for 5 days Provet SA, Lyssach, Switzerland) and with a medicated feed containing flubendazol (Flubenol 5%®, 0.15kg per 100kg feed, Provimi Kliba AG, Kaiseraugst, Switzerland) against the nematodes. In the mouth of a feral pigeon that was not used for the study, a small yellow round area in the mucosa was found - a clinical sign of trichomoniasis often referred to as “yellow button”. The microscopical examination of a crop wash in this pigeon was negative. Nevertheless, the feral pigeons were treated with dimetridazol (Chevicol®, 2.5g in 2l drinking water, chevita GmbH, Pfaffenhausen, Germany). The feral pigeons were also infested with ectoparasites and were treated with a pyrethrin spray (Acarin®, A. Ziegler AG, Stallikon, Switzerland). A PCR test for PMV1 (Paramyxovirus 1) of two pooled samples of choanal swabs was negative in the feral pigeons. PMV1 testing was not performed in the pigeons from the breeder. The pigeons from the preliminary study and the trial, did not have any contact.

5.3 Housing and feeding

Before surgery, the pigeons were kept as a group in an outdoor aviary which was 340cm wide, 540cm long and 200cm high. The purebred pigeons were kept in the same aviary as the feral pigeons, but the aviary was cleaned and disinfected in between. Branches permitted roosting of the birds. The pigeons were checked, the aviary was cleaned, and food and drinking water was provided daily by professional keepers.

After surgery, the pigeons were kept individually in boxes (46.5 cm x 55 cm x 56cm) for up to three days. A roosting bar that was wrapped with a bandage to provide better grip and comfort was fitted on the cage floor in such way that the pigeons could step on the roosting bar without flying. Food and drinking water were placed on the floor.

After up to three days, the pigeons were placed in a larger cage (114 cm x 140 cm x 155 cm) where up to 9 pigeons were kept together in order to enable social contacts. To prevent too much flying and flapping, the roosting bars were again placed on the floor. The pigeons were fed a commercial feed for homing pigeons (Landi Schweiz AG, 3293 Dotzingen, Switzerland). Drinking water was available ad libitum.

5.4 Materials

5.4.1 General surgical equipment

Common surgical equipment that was used included scalpel blades No 15, scalpel holder no 3, mosquito clamps, needle holder, and different forceps. Special instruments that were used with all three plate systems included a plate cutter with deburring device (Synthes GmbH, Oberdorf, Switzerland) to shorten the plate to the required length, a doolen bone holding clamp (Sontec Instruments, Inc., Colorado, USA) to fix the plate to the bone during drilling and an airpowered oscillating saw (Synthes GmbH, Oberdorf, Switzerland). The same double drill guide 1.0/1.3 (Synthes GmbH, Oberdorf, Switzerland) was used with all plate systems. The saw blade used was 0.25 mm thick, 6 mm wide and the usable length was 13 mm (Synthes GmbH, Oberdorf, Switzerland).

5.4.2 Preliminary study

The two feral pigeons of the preliminary study were treated identically as the pigeons of group A with the adaption plate 1.3 (see below).

5.4.3 Adaption plate 1.3, group A

Group A was treated with a stainless steel adaption plate 1.3, Compact Hand (Synthes GmbH, Oberdorf, Switzerland), which was 48 mm long with 12 holes, had a pre-bent profile, was 0.7 mm thick, 3.4 mm wide and the hole spacing was 4.0 mm (Fig. 5). Four self tapping, cruciform recessed screws with 1.3 mm thread diameter, 0.9 mm core diameter, 6 mm length and 2.4 mm head diameter were used. The plate was cut to the length of 8 holes. It was adapted to the contours of the ulna with a combined plier for plates 1.0 to 2.0, for cutting and bending (Synthes GmbH, Oberdorf Switzerland) and a bending plier 3D, left, for plates 1.0 to 2.0 with contour-bending function (Synthes GmbH, Oberdorf Switzerland). A 1.0 mm drill bit with Mini Quick Coupling was used with a mini air drill (Synthes GmbH, Oberdorf Switzerland) with a drill attachment 90˚ and a double air hose for mini air drill (Synthes GmbH, Oberdorf Switzerland). To optimize the angle for drilling a hose coupling 60˚ for mini air drill (Synthes GmbH, Oberdorf Switzerland) was used. The holes at the end of the plates were drilled as with the other plate systems. With the 1.3 adaption plate the middle screws were placed so that between them and the end screws, one hole was empty and the distance across the fracture gap was two empty holes (Fig. 6). To drive the screws into the bone a cruciform 1.3 screwdriver shaft for Mini Quick Coupling was used.

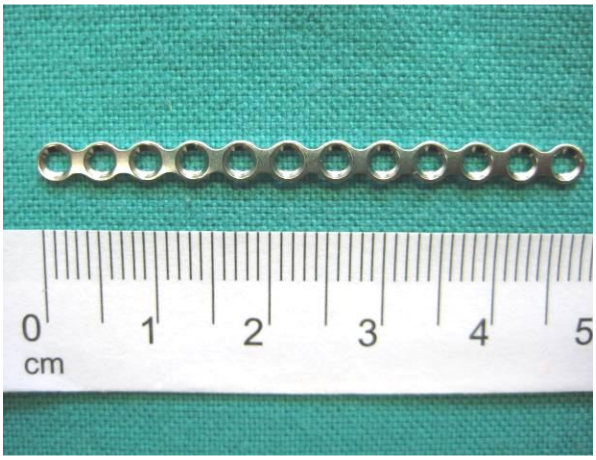

Fig. 5: Twelve hole stainless steel adaption plate 1.3, Compact Hand (Synthes GmbH, Oberdorf, Switzerland)

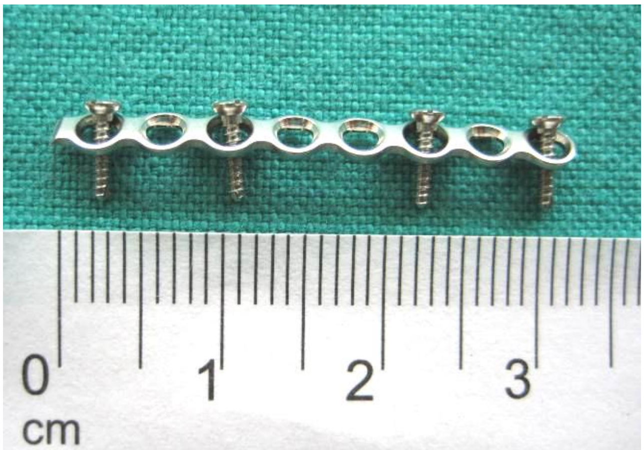

Fig. 6: Eight hole adaption plate 1.3, Compact Hand (Synthes GmbH, Oberdorf, Switzerland) with the screws placed as during surgery.

5.4.4 **Adaption plate 1.3 with washers, group B**

Group B was treated with the system 1.3 adaption plate with washers, plate and four screws as well as plate length and plate fixation technique were the same as with the 1.3 adaption plate only. Four washers (Fig. 7) were cut from the leftovers of the 1.3 adaption plate with a plate cutter with deburring device (Synthes GmbH, Oberdorf, Switzerland) and placed underneath the plate (Fig. 8).

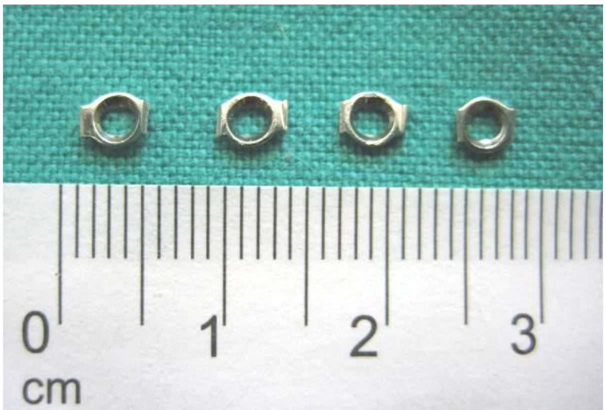

Fig. 7: Four washers cut from the leftovers of the 1.3 adaption plate (Synthes GmbH, Oberdorf, Switzerland).

Fig. 8: Washers placed underneath the 1. 3 adaption plate (Synthes GmbH, Oberdorf, Switzerland)

5.4.5 Maxillofacial miniplate, group C

Group C was treated with a maxillofacial miniplate, Compact 1.0 (Synthes GmbH, Oberdorf, Switzerland). Which is a sliceable adaption plate that has 34 holes, is 0.7mm thick and consists of pure titanium (Fig. 9). This plate had already been used in the study of Christen et al. (2005). In contrast to that study, an eleven-hole plate was used instead of a six-hole plate. Due to the malleable material, the plate could be manually adapted to the contours of the bone.

Two self-tapping titanium alloy screws were placed on each side of the fracture. The screws were 6 mm long, the core diameter was 0.7 mm, the thread diameter 1.0 mm, the thread pitch 0.25 mm, and their head diameter was 1.6 mm (Synthes GmbH, Oberdorf, Switzerland). To drill the holes, a 0.7 mm drill from a hardware store (Rolf Gabriel GmbH, Uetikon, Switzerland) was used with an airpowered AO-Drill fitted with a Jacobs chuck. The holes at the end of the plates were drilled as with the other plate systems. With the maxillofacial miniplate, Compact 1.0 the middle screws were placed so that between them and the end screws, two holes were empty, and the distance across the fracture gap was three empty holes (Fig. 10). The screws were driven in with a cruciform screwdriver shaft 1.0 with Mini Quick Coupling (Synthes GmbH, Oberdorf Switzerland).

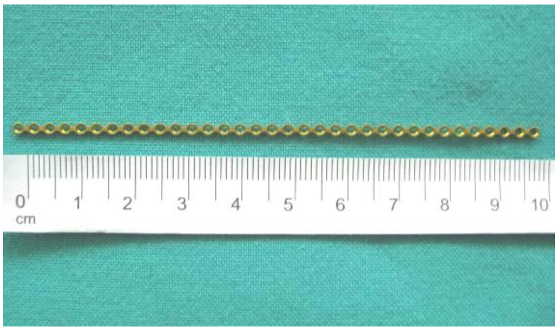

Fig. 9: A 34 hole titanium maxillofacial miniplate, compact 1.0 (Synthes GmbH, Oberdorf, Switzerland)

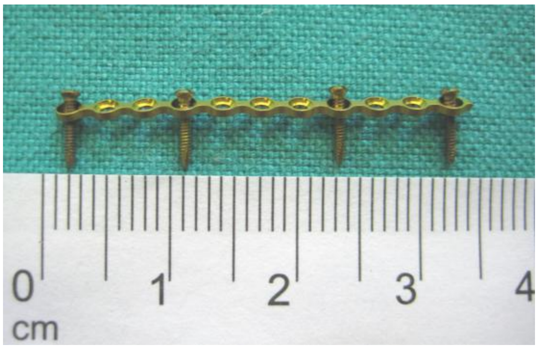

Fig. 10: Eleven hole maxillofacial miniplate, compact 1.0 (Synthes GmbH, Oberdorf, Switzerland) with the screws placed as during the surgery.

5.5 Experimental study

The three methods compared in this study were developed on dead feral pigeons. Handling of the instruments and the manual skills were also acquired practicing the surgery on several dead pigeons. The dead pigeons were provided from the population control program of the city of Zurich.

5.5.1 Anaesthesia and monitoring

Thirty minutes before surgery the pigeons were pre-medicated with carprofen (4mg/kg IM; Rimadyl®, Pfizer, Gräub AG, Bern, Switzerland). Anaesthesia was induced with 5% isoflurane (IsoFlo®, Aboot, 6341 Baar, Switzerland) via facemask. Once anesthetized, the birds were intubated with a 20AT (2 mm) sized uncuffed endotracheal tube (SurgiVet, Waukesha, USA) that was shortened to 5 cm to minimize dead space. An intravenous catheter was placed in the *Vena metatarsalis plantaris medialis* or the *Vena ulnaris* of the right wing and lactated Ringer's solution (10 ml/kg per hour iv) was administered during surgery. Butorphanol (4 mg/kg IM; Morphasol, Gräub AG, Bern, Switzerland) was given initially at the start of the surgery and was repeated after 30 minutes.

To monitor the anaesthesia, the respiratory rate and heart rate were recorded periodically. ECG, relative arterial oxygen (SpO2) and pulse rate were recorded as well. The body temperature was measured with a cloacal probe and a warm-water heating pad was used to reduce hypothermia. Anaesthesia duration and surgical duration was recorded and standard deviation was noted as (± xy).

5.5.2 Surgical preparation

The pigeons from the three groups as well as the two feral pigeons from the preliminary study were identically prepared for surgery. The feathers of the left wing except the secondary flight feathers were plucked from the dorsal and ventral site of the antebrachium. The birds were positioned in ventral recumbency with the breast on the heating pad. The wings and head were slightly elevated by positioning on a U-shaped board that provided a stable underlying for drilling and sawing. The surgical site was aseptically prepared with a chlorhexidine solution (Hibiscrub®; Globopharm AG, Küsnacht, Switzerland) and a sterile self-adherent transparent plastic sheet

(Adhesive Drape sheet; Jorgensen Laboratories, Inc., Loveland, USA) was placed on the surgical site (Fig. 11). The surgical field was approximately 5 x 3 cm (Fig. 12).

Fig. 11: Pigeon in positioned in ventral recumbency on a U-shaped board, covered with an adhesive drape sheet

Fig. 12: Surgical field (dorsal view of the left antebrachium of a pigeon)

5.5.3 **Surgical procedure**

The surgeries were started with the two pigeons from the preliminary trial with an adaption plate 1.3. The actual trial started with the adaption plate 1.3 group (group A), then the surgeries were performed on the washer group (group B) and at last on the maxillofacial miniplate group (group C). The same surgical approach as in the study of Christen et al. (2005) was used. The surgeries of the three groups were analogue. They differed only in the implant, screws and the drill size. The dorsal approach to the radius and ulna was used as recommended by Martin and Ritchie (1994). The skin incision was made just cranially to the insertion point of the secondary flight feathers and dorsocranially to the left ulna (Fig. 13). The ulna was bluntly dissected with a surgical clamp (Fig. 14). The plates were cut to approximately 2/3 of the bone length with a plate cutter. The 1.3 adaption plates were cut to the length of eight screw holes and the maxillofacial miniplates to eleven screw holes. The leftovers of the 1.3 adaption plates of the washer group were cut to four washers. Because the ulna is slightly curved, the plates were bent to obtain optimal contact to the bone. With the maxillofacial miniplates manual bending was possible (Fig. 15) while for the 1.3 adaption plates combined plier for plates 1.0 to 2.0, for cutting and bending and a bending plier 3D, left, for plates 1.0 to 2.0 with contour-

bending function was used. The plates were positioned as accurately as possible (Fig. 16) and secured to the bone with a Doolen bone holding clamp (Fig. 17).
With all plate systems four screw holes were drilled into the ulna. The same double drill guide 1.0/1.3 was used with all plate systems. During drilling the bone was cooled with physiologic saline solution (Fig. 18). The plate was then removed again. In Fig. 19 the drilled holes in the ulna are visible. After drilling of the holes, the radius was bluntly dissected. Thereafter fractures of the radius and the ulna were produced by transecting the diaphysis with an oscillating bone saw (blade width 6 mm, thickness 0.25 mm) (Fig. 20). Only the ulna was fixated with one of the three plating systems. The radial fragments were not stabilized. At first, the distal bone fragment was fixated (Fig. 21), then the screws were placed into the proximal fragment of the ulna. For the plating system with washers the washers were placed with forceps between the screw hole and the plate before the screws were driven into the ulna. After tightening the screws once again, the skin was closed with a 4-0 polyglactin 910 (Vicryl®; Ethicon GmbH, Norderstedt, Germany) in a standard one layer, simple continuous pattern (Fig. 22).

Fig. 13: Skin incision cranial to the secondary flight feathers and dorsocranial to the ulna

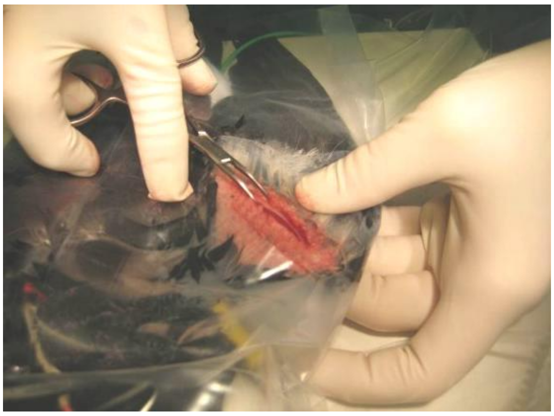

Fig. 14: Blunt dissection of the ulna

Fig. 15: Manual bending of a maxillofacial miniplate, Compact 1.0 (Synthes GmbH, Oberdorf, Switzerland)

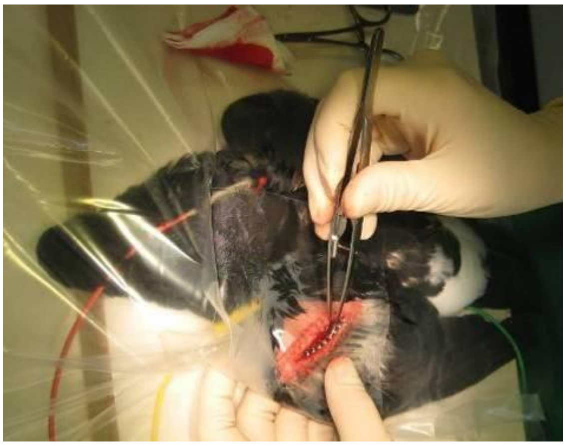

Fig. 16: Accurate positioning of a 1.3 adaption plate (Synthes GmbH, Oberdorf, Switzerland)

Fig. 17: Securing of a 1.3 adaption plate to the ulna with a Doolen bone holding clamp (Sontec Instruments, Inc., Colorado, USA).

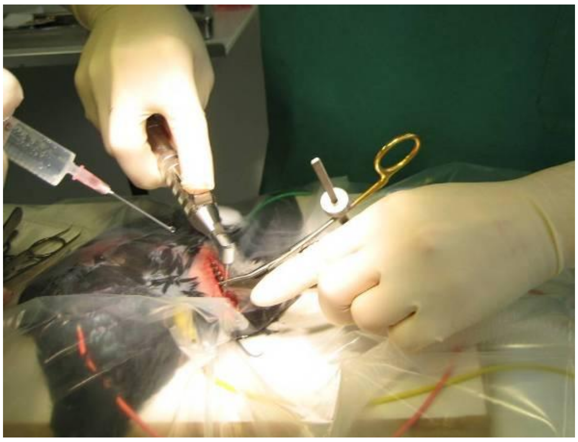

Fig. 18: Drilling of holes for the 1.3 adaption plate with a 1.0 mm drill and a double drill guide 1.0/1.3 (Synthes GmbH, Oberdorf, Switzerland) and cooling with physiologic saline solution delivered by syringe.

Fig. 19: Ulna with drilled holes

Fig. 20: Ulna that was transsected with an oscillating bone saw

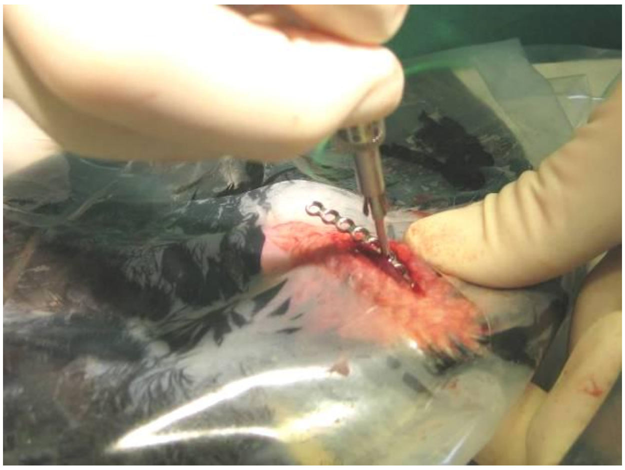

Fig. 21: Placing screws into the distal bone fragment. Here a stainless steel 1.3 adaption plate (Synthes GmbH, Oberdorf, Switzerland).

Fig. 22: Skin closure with 4-0 polyglactin 910 (Vicryl®; Ethicon GmbH, Norderstedt, Germany) in a standard one layer, simple continuous pattern. Here a fracture fixation with a 1.3 adaption plate (Synthes GmbH, Oberdorf, Switzerland).

5.6 Postoperative care

After the surgery the wing was not bandaged to prevent shortening of the propatagium. The activity was minimized by separation and cage rest. The animals were handled as little as possible to prevent them from flapping with the wings. To administer the analgesic the pigeons were gently wrapped in a towel to preserve the recently fixated wing from too much motion. Analgesia was provided with carprofen (4mg/kg IM; Rimadyl®, Pfizer, Gräub A, Bern, Switzerland) for 3 days. Chlortetracycline (1 g in 1l drinking water; Chlortetracyclin+®, chevita GmbH, Pfaffenhausen, Germany) was administered as antibiotic treatment for 7 – 10 days.

5.7 Healing assessment

5.7.1 Clinical examination

Following surgery the general condition was checked daily by professional keepers or the surgeon. The wing was palpated, the body condition was evaluated and the scar was examined two and four weeks after surgery.

After four weeks, the flight ability of the pigeons was assessed. The birds were put in an aviary (340cm wide, 540cm long and 200cm high). Flight ability was classified in three categories: good flight ability (no problems to fly from the ground up to the roosting bars in 130 -150 cm height), moderate flight abilities (only waist-high flying), poor flight ability (only knee-high flying)

5.7.2 Radiological evaluation

Radiographs were taken before and immediately after the surgery, and again two and four weeks after surgery. The two birds of the preliminary study were an exception: they were not x-rayed 14 days post surgery.

For the radiograph four weeks after surgery, the birds were anesthetized with isoflurane (IsoFlo® Abbott AG, Gräub AG, Bern, Switzerland) or dead. For an overview ventro-dorsal projection, the birds were positioned on a restraint board (Miami Vise Avian Restraint; Veterinary specialty Products, Inc. FL, USA). Additionally, a caudo-dorsal projection of the left wing was made under manual restraint. Digital radiography was used with the settings 40 kV and 6.3 mAs. The radiographs were evaluated in collaboration with a radiologist. For evaluation and measurements, the OsiriX Imaging Software (OsiriX Foundation, Geneva, Switzerland) was used. The radiographs before the surgery were checked for any abnormalities. The radiographs taken immediately after the surgery as well as two and four weeks after surgery were classified into the following categories:

- Plate: bending, twisting or fracture of the plate
- Screws: screws bicortical, loosening of screws
- Osteomyelitis and additional fractures
- Reduction of the fracture ends of the ulna: cortices aligned, overlap of the fracture ends greater than 50% aligned, less than 50% aligned, no fracture ends visible because of callus formation

- Angle of the fracture ends of the ulna in degrees. The angle was measured at the intersection of a line from the centre of the distal trochlea of the ulna to the centre of the osteotomy site and a line from the centre of the osteotomy site to the center of the proximal ulna. The values were indicated in mean degrees with their standard deviation for each group.
- Fracture gap of the ulna: The fracture gap was measured in millimetres at the caudal aspect of the ulna. The mean gap and the standard deviation were calculated for each group.
- Width of mineralised callus: The width of the mineralised callus was measured in millimetres at the caudal surface of the ulna at the fracture site. The mean callus formation and the standard deviation were calculated for each group.
- Bone: The bone of the ulna was measured in millimetres 14 days after the surgery proximal to the fracture site, where the cortex remained normal. The mean cortex diameter and the standard deviation was calculated for all pigeons.
- Callus formation was not evaluated in the same way as in the study of Christen et al. (2005). In that study, cortex diameter and mineralized callus width were measured in the radiographs, and the ratio of these values was calculated. Afterwards, the birds were separated into four categories of callus to cortex ratio. In the present study, measurements of cortex diameter turned out to be very inconsistent and hardly reproducible. Therefore, in the present study, the entire callus including the ulna and the bone width at the distal end of the ulna where the cortices are again parallel were measured (Fig. 22). A ratio of these values was calculated.

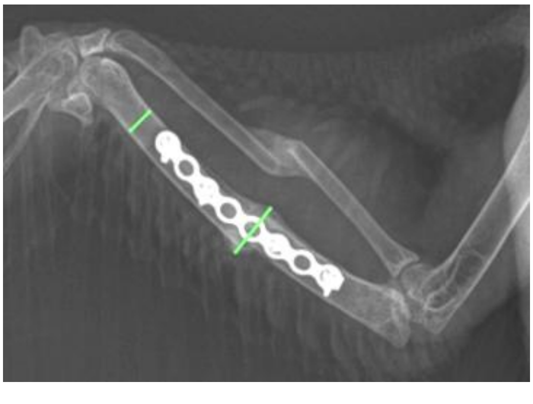

Fig. 23: Callus formation including the ulna was measured at the fracture site and a ratio was calculated with the bone width measured at the distal end of the ulna.

- Subjective impression of the fixated wing and the fracture healing: classification as, “poor”, “moderate” and “good”.
- The percentage of pigeons of a group relates to the actual number of pigeons 14 and 28 days after the surgery (Tab. 5).

5.7.3 Post mortem examination

All pigeons were euthanized four weeks after surgery with pentobarbital by intravenous injection (Eskonarkon®, Streuli Pharma AG, Uznach, Switzerland) under inhalation anaesthesia with isofluran. The birds were weighed and the ulna and radius were dissected. It was noted whether the plate was distorted and bent, torn out of position, overgrown with callus, and whether it was easy to remove the plate. Callus size, bone width proximal and distal of the callus and the length of radius and ulna were measured with an electronic digital calliper (technocraft® industries, India).

5.7.4 Statistics

Data are represented as mean (± SD). Groups were compared by one-way ANOVA with Sidak post hoc tests if measurements had normal distribution, and by Kruskal-Wallis-test and subsequent pair-wise Mann-Whitney U-tests (with Sidak adjustment for multiple testing) if not. All analyses were performed in SPSS 16.0 (SPSS Inc. Chicago, IL). The significance level was set to 0.05.

6 Results

6.1 Surgical technique and plate application

Mean anaesthesia duration of the two feral pigeons of the preliminary study was 81 min (±12.7min). Mean anaesthesia duration of the actual study was 56 min (± 9.5 min) with the adaption plate 1.3 group (group A), 54 min (± 3.8 min) with the washer group (group B) and 59 min (± 8.0 min) with the maxillofacial miniplate group (group C). Anaesthesia duration was not significantly different between the three groups (ANOVA, p=0.554). Mean surgical time was 38.5 min (± 9.2 min) in the pigeons of the preliminary study, 37 min (± 3.9 min) with group A (adaption plate 1.3), 38.5 min (± 1.9 min) with group B (washers) and 40 min (± 9.0 min) with group C (maxillofacial miniplate). Also surgical time did not differ significantly between the groups (Anova p=0.671). Surgical technique differed only minimally and the difficulty of application was similar to the subjective opinion of the surgeon (Appendix I).

6.2 Surgical procedure

6.2.1 Preliminary study

The application of the adaption plate 1.3 to the two feral pigeons was uneventful (Appendix I).

6.2.2 Adaption plate 1.3, group A

In three of 6 pigeons surgery was uneventful. Soft tissue was moderately traumatised with the oscillating bone saw in pigeon 2B and one screw was placed obliquely instead of perpendicular to the two cortices. In pigeon 12B the most distal screw was slightly loose and in pigeon 14B there were difficulties to put in the most proximal screw; therefore, an additional screw hole was drilled more distally. In pigeon 22B one screw was placed into the wrong plate hole by mistake, although surgery was uneventful (Appendix I).

6.2.3 Adaption plate 1.3 with washers, group B

Surgery was uneventful in all six pigeons (Appendix I).

6.2.4 Maxillofacial miniplate, group C

In five of six pigeons surgery was uneventful. In pigeons 8B there were minor difficulties to put in the most distal screw, but after several approaches the screw was put through both cortices (Appendix I).

6.3 Postsurgical condition

6.3.1 Preliminary study

The postsurgical period was uneventful (Appendix I).

6.3.2 Adaption plate 1.3, group A

One pigeon flapped excessively with the wings the day after surgery during handling for the carprofen injection. It was the pigeon (12B) mentioned above with the loose most distal screw. After flapping the ulna was unstable at palpatory examination and the implant loose. This pigeon was euthanized for animal welfare reasons (Tab. 5). Pigeon 1B flapped as well after awaking from anaesthesia, but the fixated wing did not seem damaged on palpation. Postsurgical period was uneventful in the other four pigeons of this group (Appendix I).

6.3.3 Adaption plate 1.3 with washers, group B

Two pigeons flapped excessively with the wings during handling two or three days after the surgery, respectively. This could not be prevented, in spite of very careful handling with a towel. These two pigeons were euthanized (Tab. 5). In the other pigeons of group B, the postsurgical time was uneventful (Appendix I).

6.3.4 Maxillofacial miniplate, group C

The postsurgical period was uneventful. No pigeon was euthanized during the periode of the study (Tab. 5) (Appendix I).

Tab. 5: Number of pigeons in the three different groups (A, B and C) immediately postoperative, 14 and 28 days after the surgery. In group A and B pigeons had to be euthanized because of implant failure.

	post op	14 days after surgery	28 days after surgery
adaption plate 1.3 (A)	6	5	5
washer (B)	6	4	4
maxillofacial miniplate (C)	6	6	6

6.4 General condition and flight ability four weeks after surgery

After the surgeries general condition and behaviour were within normal limits. The pigeons were feeding normally, were active and showed courtship behaviour; some females laid eggs. One pigeon was pecking the others and was therefore separated. No pigeon showed apathy or anorexia. All pigeons remained in good body condition after the surgery. The wing was stable at palpatory examination four weeks after surgery in all pigeons except one pigeon of group B. During the x-ray examination two weeks after surgery instability of the wing was not noticed. Tab. 6 shows a summary of the assessed flight ability of the three groups.

6.4.1 Adaption plate 1.3, group A

Flight ability was considered good in all five remaining pigeons (100%) of group A. They reached the roosting bars in 130-150cm height without problems.

6.4.2 Adaption plate 1.3 with washers, group B

In two of four remaining pigeons (50%) of the washer group flight ability was good. The flight ability of another pigeon of the washer group (25%) was moderate. It could not reach the roosting bars and flew only waist-high. In one pigeon of the washer group (25%) flight ability was not assessed because the plate was protruding through the skin and the wing unstable four weeks after surgery. Two weeks after surgery the plate was still in position.

6.4.3 Maxillofacial miniplate, group C

From group C two of six pigeons (33%) showed moderate flight ability (waist-high flying) while four of six pigeons (67%) flew poorly. The pigeons with poor flight ability were only fluttering knee-height.

6.4.4 Statistical analysis

After 28 days, there was a significant difference in the flight ability between the groups (Kruskal-Wallis $p=0.005$). After adjustment for multiple testing, the difference between group A and C was significant, between group B and C the difference only tended towards significance.

Tab. 6: Flight ability in pigeons four weeks after surgery. The percentage is referring to the actual number of pigeons of the group four weeks after the surgery. The actual number of pigeons at that time is indicated in Tab 5

Flight ability	Adaption plate 1.3	Adaption plate 1.3 with washers	Maxillofacial miniplate, Compact 1.0
Good flight ability (no problems to fly to the roosting bars in 130 -150 cm height)	5 (100%)	2 (50%))	0 (0%)
Moderate flight ability (only waist-high flying)	0 (0%)	1 (25%)	2 (33%)
Poor flight ability (only knee-high flying)	0 (0%)	0 (0%)	4 (67%)
No assessment of flight ability	0 (0%)	1 (25%)	0 (0%)

6.5 Radiological evaluation

6.5.1.1 Radiographs before the surgery

All radiographs taken of the pigeons taken before the surgery were unremarkable in both projections (Fig. 24).

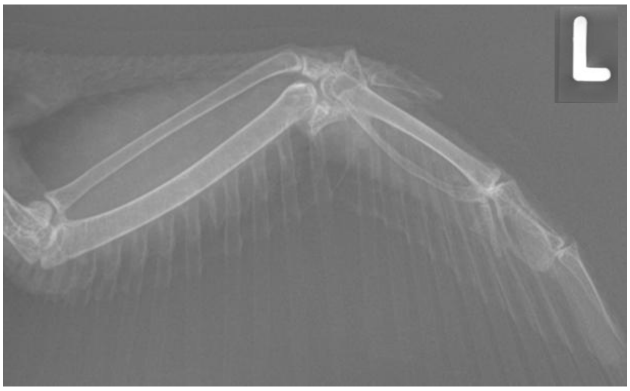

Fig. 24: Control radiographs of pigeons taken before the surgery

6.5.2 **Plate**

6.5.2.1 Preliminary study

The adaption plate 1.3 was unchanged immediately after surgery and 28 days after surgery when x-rayed again (Appendix IIa, IVa).

6.5.2.2 Adaption plate 1.3, group A

In group A the adaption plate 1.3 was unchanged immediately after surgery (Fig. 25) as well as after 14 (Fig. 26) and after 28 days (Fig. 27) (Appendix IaI, IIIa, IVa).

6.5.2.3 Adaption plate 1.3 with washers, group B

Also in group B there was no change in the adaption plate 1.3 immediately after surgery (Fig. 28), after 14 (Fig. 29) and after 28 days (Fig. 30) (Appendix IIb, IIIb, IVb).

6.5.2.4 Maxillofacial miniplate, group C

Immediately after surgery the maxillofacial miniplates were only slightly bent to adapt to the contours of the ulna (Fig. 31). However all maxillofacial miniplates were bent and twisted at day 14 (Fig. 32) and day 28 (Fig. 33). In one case the maxillofacial miniplate was even fractured at the sixth hole at day 28 (Appendix IIc, IIIc, IVc).

6.5.2.5 Statistical analysis

There was no significant difference between the three groups in plate bending directly post surgery. Fourteen days after surgery, the plate bending score differed significantly between the groups (Kruskal-Wallis $p=0.001$). After adjustment for multiple testing, the difference between group C and the other two groups were significant. After 28 days, this situation had not changed (Kruskal-Wallis $p=0.001$) and the difference between group C and the other two groups remained significant.

Fig. 25: Radiograph immediately after surgery of a pigeon of group A. The plate is intact and all four screws are bicortical.

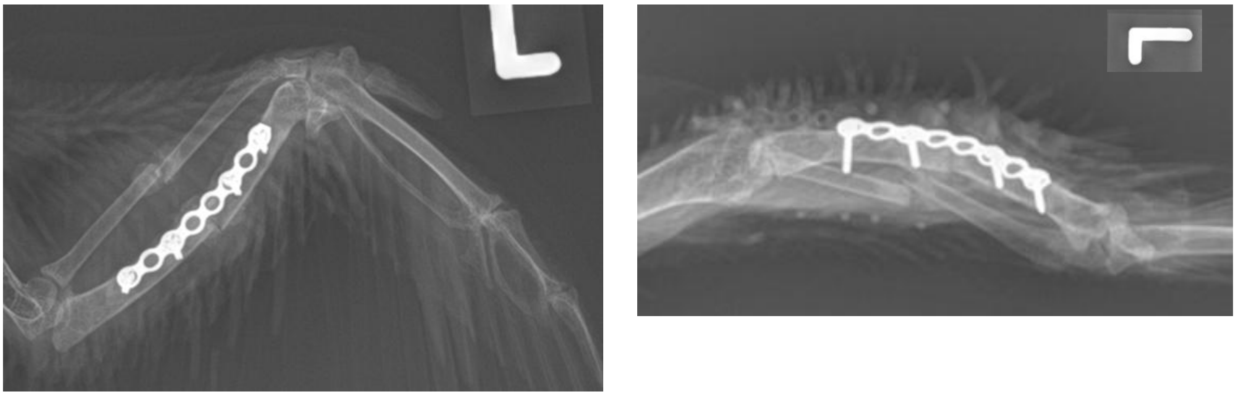

Fig. 26: Radiograph 14 days after surgery of a pigeon of group A. Minor callus formation is visible.

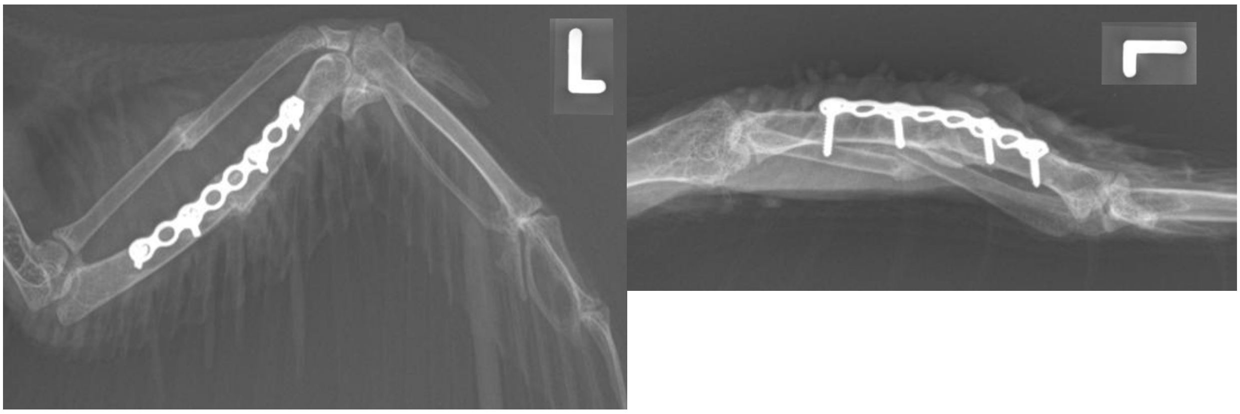

Fig. 27: Radiograph 28 days after surgery of a pigeon of group A. Bending or distortion did not occur. All screws remained bicortical in this pigeon.

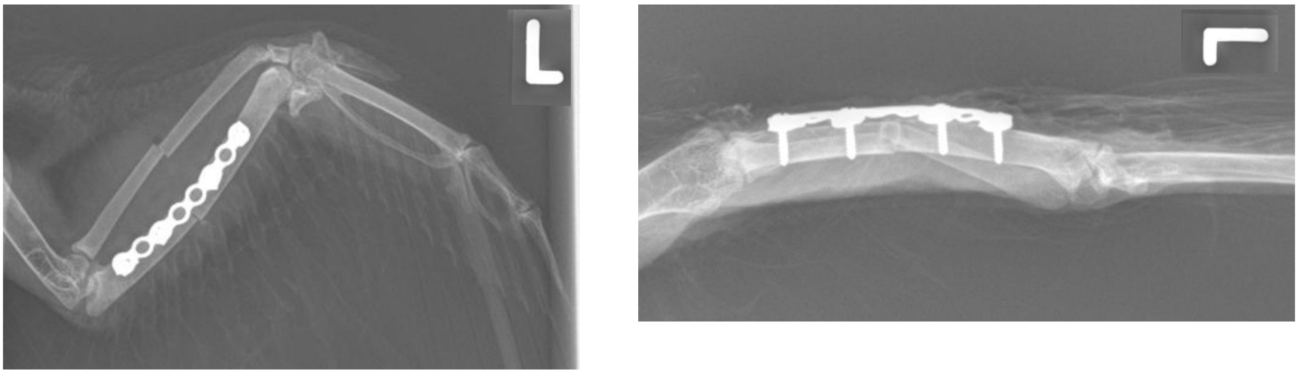

Fig. 28: Radiograph immediately after surgery of a pigeon of group B. The washers are best visible in the caudocranial projection. All screws are bicortical.

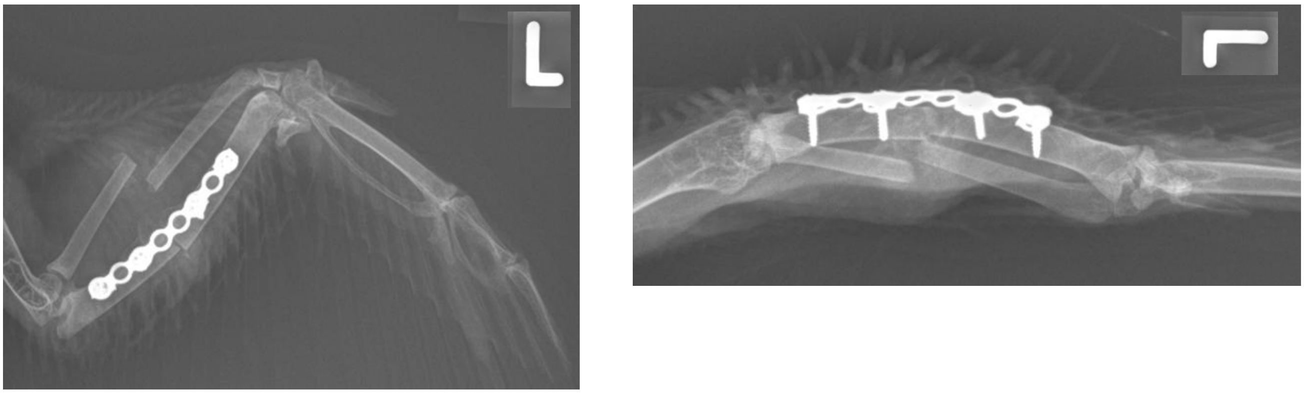

Fig. 29: Radiograph 14 days after surgery of a pigeon group B. The plate is unchanged. Slight callus formation is visible.

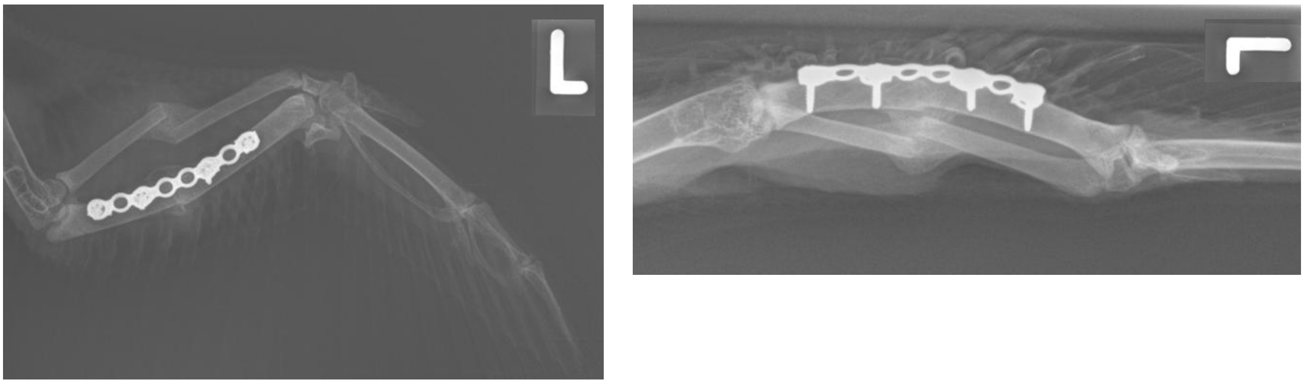

Fig. 30: Radiograph 28 days after surgery of a pigeon of group B. Plate bending or distortion did not occur. Callus formation is clearly visible.

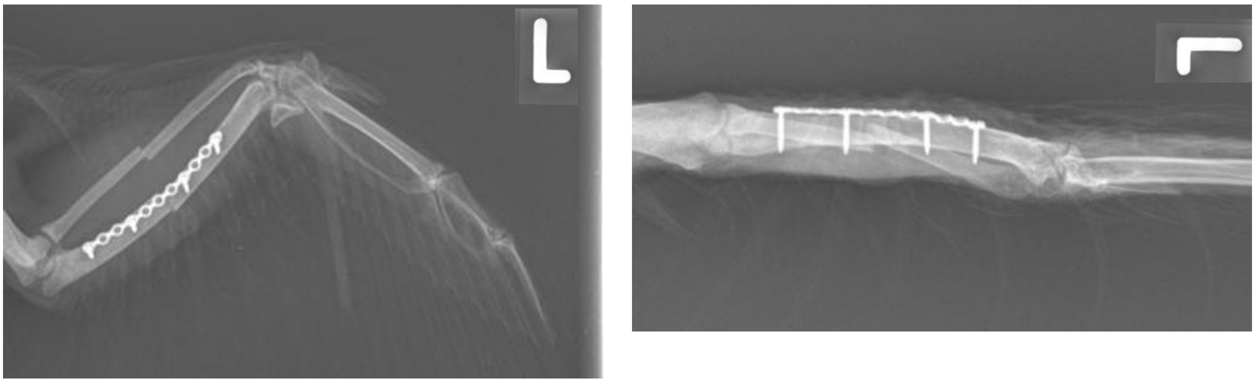

Fig. 31: Radiograph immediately after surgery of a pigeon of group C. The plate was neither twisted nor bent. It was only adapted to the contours of the ulna.

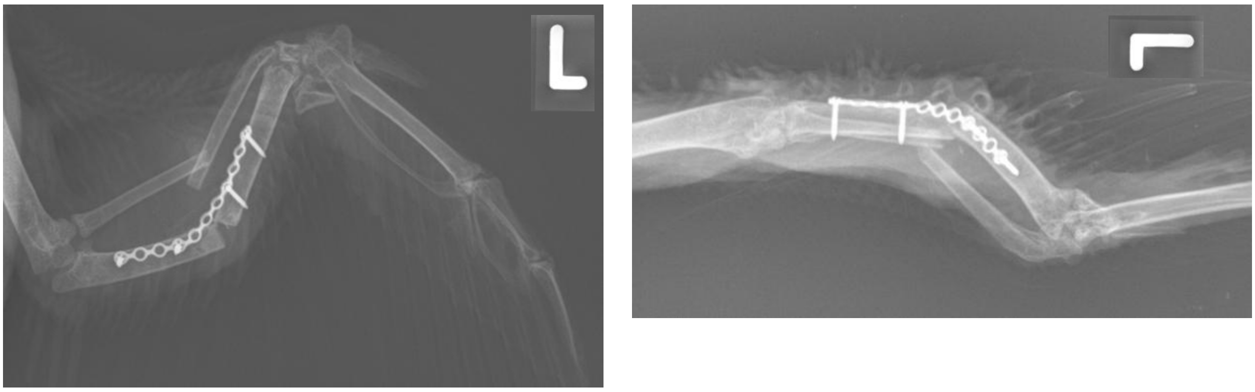

Fig. 32: Radiograph 14 days after surgery of a pigeon of group C. The plate was twisted and bent nevertheless the screws remained bicortical. The angle of the ulna cranial at the fracture site is smaller compared to the angle in group A and B. The fracture gap at the caudal surface of the ulna is wider compared to group A and B.

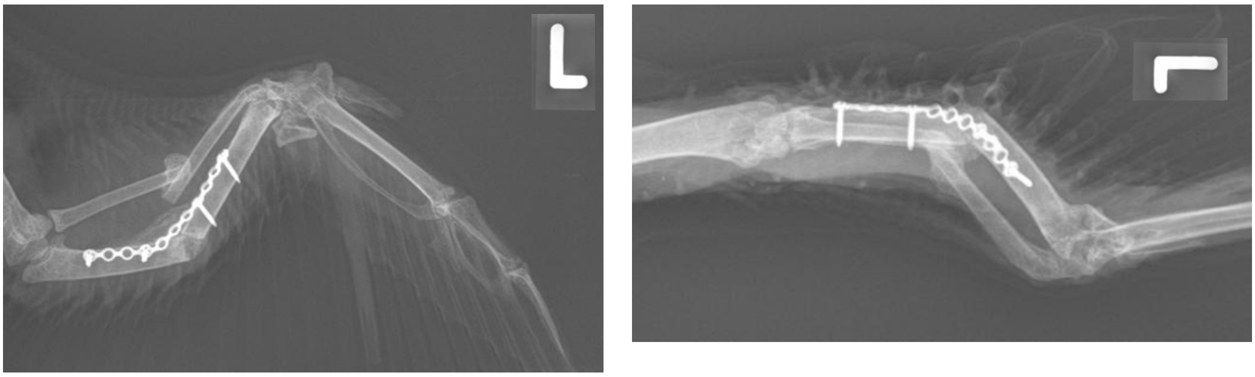

Fig. 33: Radiograph 28 days after surgery of a pigeon of group C. The plate was bent and twisted, all screws remained bicortical. Callus formation occurred mainly at the cranial site of the ulna.

6.5.2.6 Screw score

Whether all four screws of a pigeon were positioned bicortical, and whether they remained bicortical for 14 and 28 days after the surgery, is summarized in Fig. 34. In the two pigeons of the preliminary study, all screws were bicortical in the radiograph immediately after surgery. After four weeks, none of the screws were bicortical any more. In 50% of the pigeons of group A (adaption plate 1.3), all screws were bicortical immediately after surgery, and after 14 and 28 days in 40% of the pigeons all screws remained bicortical. In only 30% of all pigeons of the washer group (group B) all screws were bicortical immediately after surgery. After 14 and 28 days there was no pigeon with all screws remaining bicortical. In the group with the maxillofacial miniplates (group C) all four screws were positioned bicortical in 100% of the pigeons and remained bicortical for 14 and 28 days after the surgery in spite of plate distortion, bending and in one case even in spite of plate fracture. An example of retraction of screws and even loss of one screw in a pigeon of group B 14 days after surgery is given in Fig. 35. Four weeks after surgery, the implant was almost unchanged although the most proximal screw was lost and the second and third proximal screw loosened and retracted (Fig. 36). The loss of the screw before day 14 may indicate that the screw was not well positioned in the first place.

6.5.2.7 Statistical analysis

Directly after surgery, the screw score tended to differ between the groups (Kruskal-Wallis p=0.057), with differences between group C and the other two groups tending towards significance after adjustment for multiple testing.

Fourteen days after surgery, the screw score differed significantly between the groups (Kruskal-Wallis p=0.009), with no difference between group A and B, and the difference between group B and C being significant and that between group A and B tending towards significance after adjustment for multiple testing.

Twenty-eight days after surgery, the situation was exactly the same: the screw score differed significantly between the groups (Kruskal-Wallis p=0.009), with no difference between group A and B, and the difference between group B and C being significant and that between group A and C tending towards significance after adjustment for multiple testing.

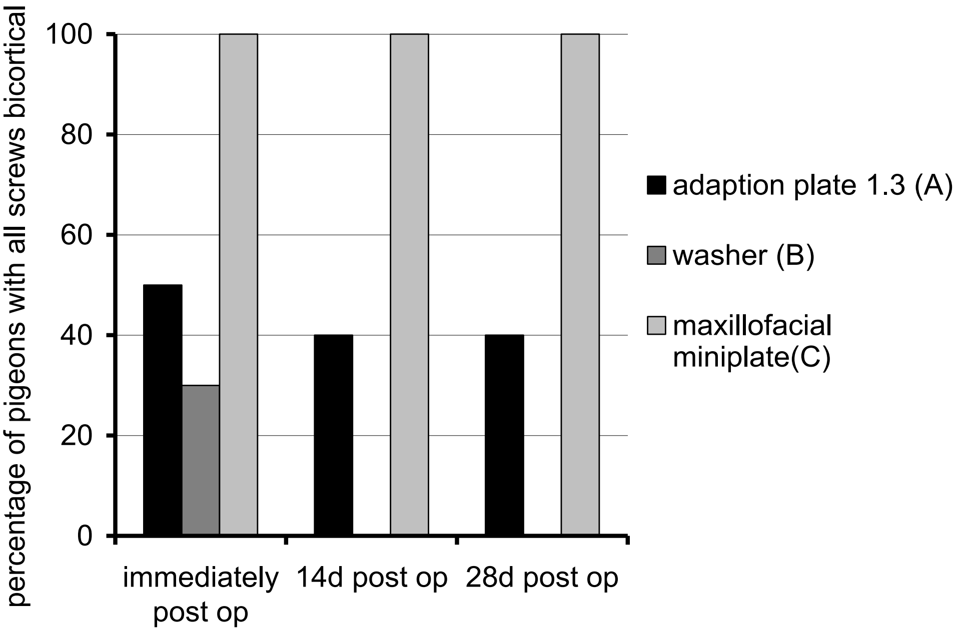

Fig. 34: Percentage of pigeons of a group in which all screws were bicortical in the radiograph immediately postoperative, 14 days and 28 days after surgery.

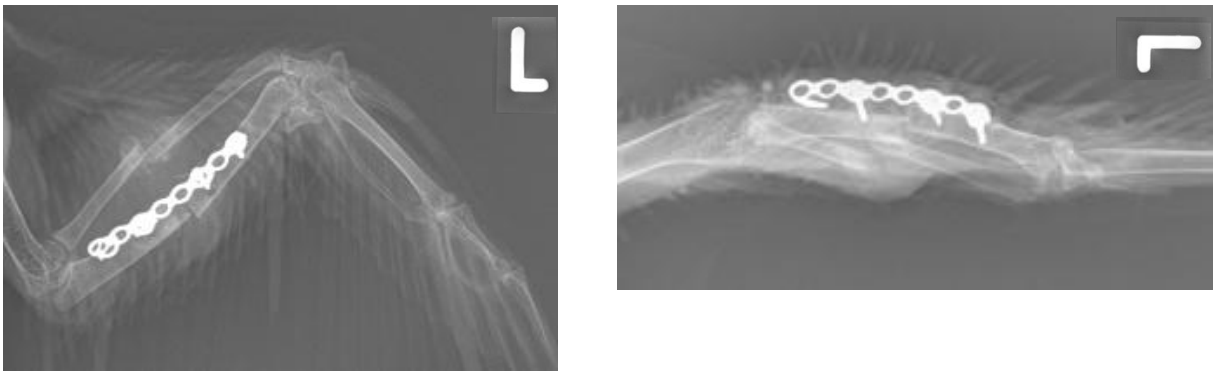

Fig. 35: Radiograph 14 days after surgery of a pigeon of group B with loss of the most proximal screw and retraction of the three remaining screws.

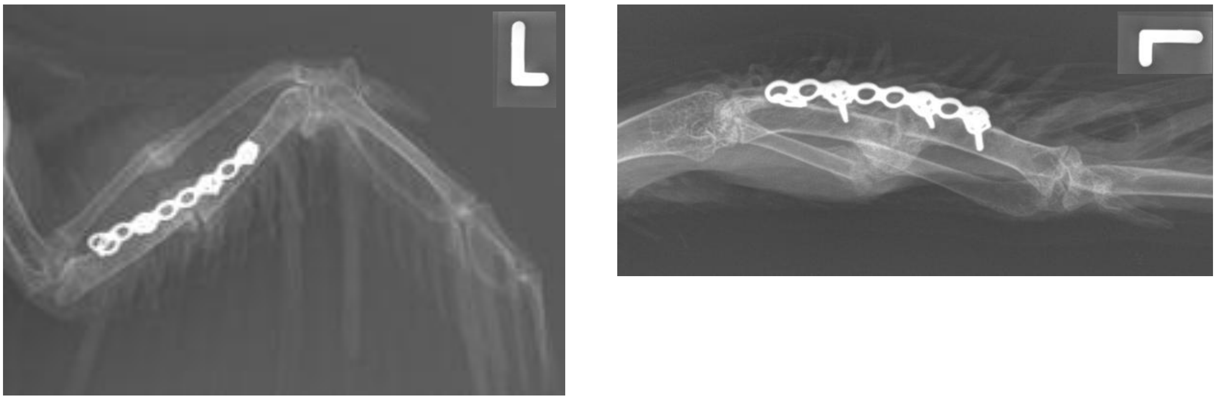

Fig. 36: Radiograph 28 days after surgery of the same pigeon of group B as in Fig. 34. The implant and screw position almost did not change although the most proximal screw was lost and the second and third proximal screw loosened and retracted.

6.5.3 **Osteomyelitis and additional fracture**

6.5.3.1 Preliminary study

There was no case of osteomyelitis or additional fractures (Appendix IIa, IVa).

6.5.3.2 Adaption plate 1.3, group A

In one pigeon the post proximal screw could not be placed in the most proximal screw hole during the surgery and was placed in the second proximal hole. This pigeon showed indistinct periosteal and endosteal surfaces indicative for osteomyelitis 14 days after surgery. In the same pigeon an additional fracture was present in the proximal ulna. The osteomyelitis was resolved 28 days after surgery and the fracture was healed (Appendix IIa, IIIa, IVa).

In another pigeon of this group an additional central segmental fracture from the proximal ulnar portion was present. This pigeon showed delayed callus formation 14 days after surgery but progressive healing at day 28.

6.5.3.3 Adaption plate 1.3 with washers, group B

One pigeon showed irregular periosteal reactions as well as lucency around the screws 14 days after surgery. Twenty-eight days after surgery the osteomyelitis had advanced to progressive bone lysis and incomplete callus formation (Appendix IIb, IIIb, IVb).

6.5.3.4 Maxillofacial miniplate, group C

In one pigeon osteomyelitis did not appear until 28 days after surgery. On the radiograph lucency around the plate and callus formation but incomplete bridging of the fracture gap was visible (Appendix IIc, IIIc, IVc).

6.5.4 **Reduction of the fracture ends of the ulna**

6.5.4.1 Adaption plate 1.3, group A

Immediately after surgery the fracture ends were aligned in 50 % of the pigeons of group A (Fig. 37). In 33.3% of the pigeons of group A overlap of the fracture ends was greater than 50%. Only in one pigeon of group A (16.7%) was the overlap of the cortices of the ulna less than 50%. Two weeks after surgery, the cortices remained aligned only in 40% of the pigeons of group A (Fig. 38). In 40% of the pigeons, the overlap was greater than 50% and in 20% overlap was less than 50%. Four weeks after surgery, the cortices remained aligned in 20% of the pigeons of group A (Fig. 39). In 40% overlap was greater than 50% and in 20% overlap was less than 50%. In one pigeon (20%) the fracture ends were not visible anymore because of callus formation (Appendix IIa, IIIa, IVa).

6.5.4.2 Adaption plate 1.3, washer, group B

In 33% of the pigeons the fracture was aligned immediately after surgery and in 66.7% overlap was greater than 50%. Two weeks after surgery overlap of the fracture ends was greater than 50%. Four weeks post surgery overlap of the fracture ends was greater than 50% in 50% of the pigeons, overlap of the fracture ends was less than 50% in 25% of the pigeons, and in one pigeon (25%) the fracture ends were not visible because of callus formation (Appendix IIb, IIIb, IVb).

6.5.4.3 Maxillofacial miniplate, group C

Immediately after surgery the fracture ends were aligned in 67% of the pigeons of group C and in 33% overlap of the fracture ends was greater than 50%. Two and four weeks after surgery in 100% of the pigeons the fractures ends remained at greater than 50% overlap (Appendix IIc, IIIc, IVc).

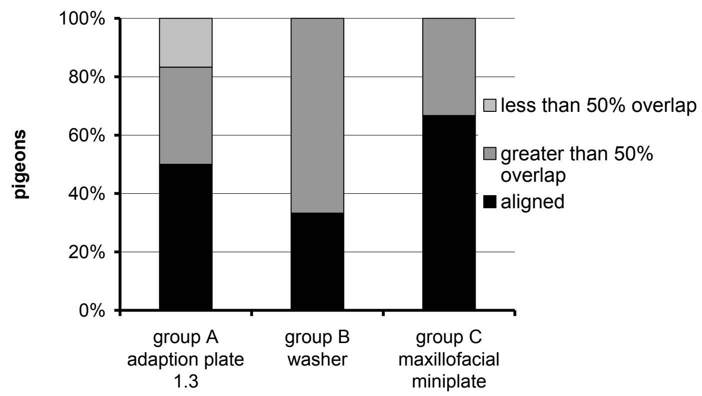

Fig. 37: Alignment of the ulna immediately after surgery. Alignment was classified into the categories aligned, greater than 50% overlap, less than 50% overlap. The percentage relates to the number of animals of the group at this moment.

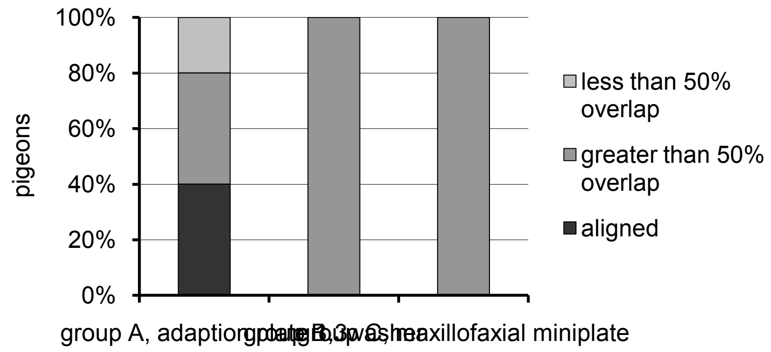

Fig. 38: Alignment of the ulna 14 days after surgery. Alignment was classified as aligned, greater than 50% overlap and less than 50% overlap. The percentage relates to the number of animals of the group at this moment.

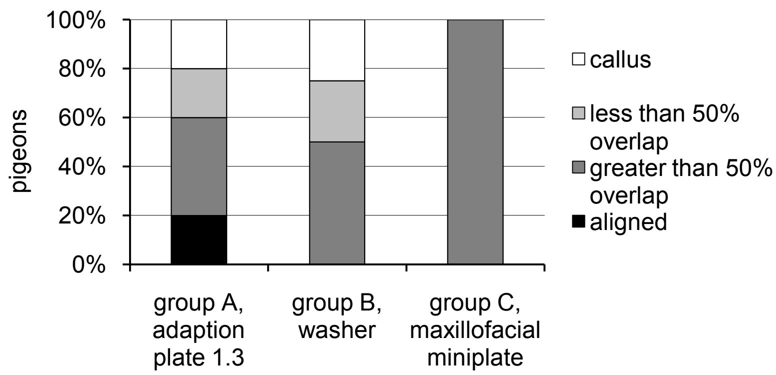

Fig. 39: Alignment of the ulna 28 days after the surgery. Callus was added as an additional classification to the "categories" used in Tab. 36 and 37 for cases where the fracture ends could not be identified anymore. The percentage relates to the number of animals of the group at this moment.

6.5.5 Angle of the fracture ends of the ulna

6.5.5.1 Adaption plate 1.3, group A and Adaption plate 1.3 with washers, group B

In group A and B the angle of the fracture ends almost remained constant at about 160° after two and four weeks (Fig. 40) (Appendix IIa/b, IIIa/b, IVa/b).

6.5.5.2 Maxillofacial miniplate, group C

In group C the mean angle of the fracture ends decreased from 160° ± 2.0° to 134° ± 6.7° after two weeks and only slightly increased to 136° ± 6.3° after four weeks (Fig. 40) (Appendix IIc, IIIc, IVc).

6.5.5.3 Statistical analysis

There was no significant difference in the angle between the three groups (A, B, and C) after the surgery (ANOVA p=0.296). Fourteen and 28 days after surgery, the difference in the angle between group C (maxillofacial plate) and the other two groups was significant (ANOVA p<0.0001 in both cases) (Appendix II).

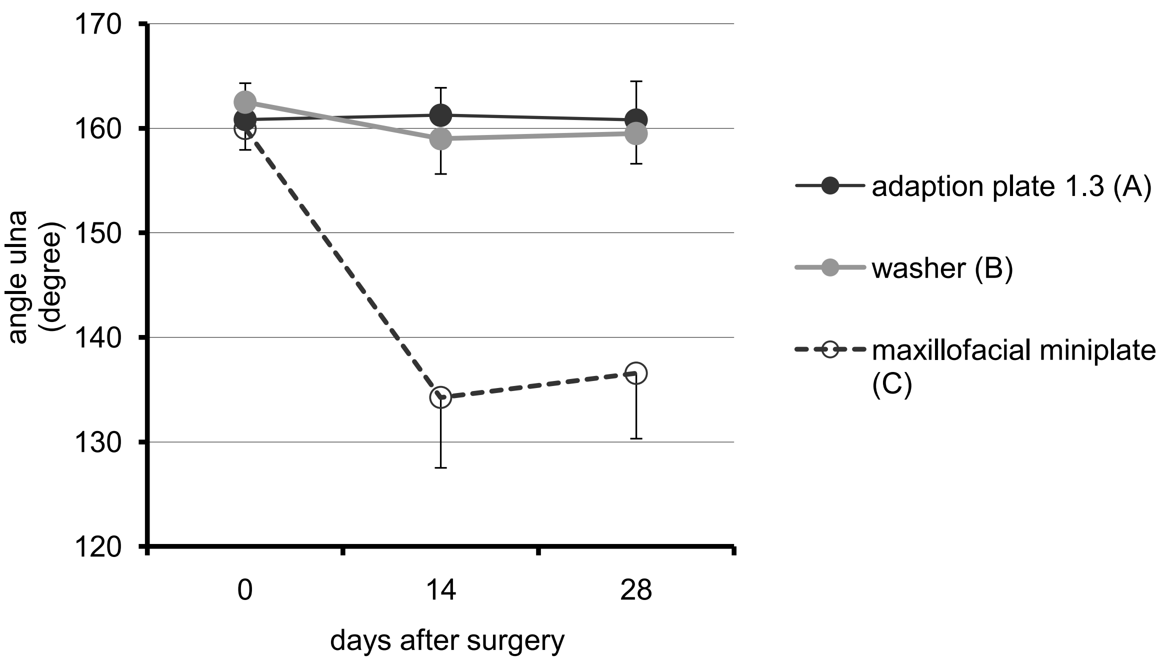

Fig. 40: The mean angle and its standard deviation of fracture ends of the ulna measured in the groups A, B and C immediately after surgery as well as two and four weeks later.

6.5.6 **Fracture gap of the ulna**

6.5.6.1 Adaption plate, group A

In group A the mean fracture gap was 0.43 mm ± 0.2 mm immediately after surgery (Fig. 41). Two weeks later the mean fracture gap was slightly increased (0.66 mm ± 0.46). In one pigeon the fracture gap could not be clearly identified two weeks after the surgery because of an additional fracture, and in another pigeon the fracture gap was widened and the fracture margins irregular. Four weeks after the surgery the fracture gap was filled with callus in all pigeons and could not be measured anymore (Appendix IIa, IIIa, IVa).

6.5.6.2 Adaption plate 1.3 with washers, group B

In group B the mean fracture gap measured 0.31 mm ± 0.27 mm immediately after surgery. After two weeks the fracture gap was also slightly increased and measured 0.63 mm ± 0.18 mm. Four weeks after surgery the fracture gap was smaller than immediately after surgery at 0.18 mm ± 0.23 mm (Fig. 41) (Appendix IIb, IIIb, IVb).

6.5.6.3 Maxillofacial miniplate, group C

In group C the mean fracture gap measured 0.42 mm ± 0.19 mm immediately after surgery. Because all maxillofacial miniplates bent, the fracture gap increased at the caudal aspect of the ulna. Two weeks after surgery the fracture gap was significantly more increased than in group A and B and measured 1.57 mm ± 0.63 mm. After four weeks the fracture gap at the caudal aspect of the ulna measured 1.31 mm ± 0.84 mm (Fig. 41) (Appendix IIc, IIIc, IVc).

6.5.6.4 Statistical analysis

There was no difference in the gap between the three groups (A, B and C) immediately after surgery (ANOVA p=0.568). Fourteen and 28 days after surgery, the difference in the gap between group C and the other two groups was significant (ANOVA 14 days p=0.018; 28 days p=0.004).

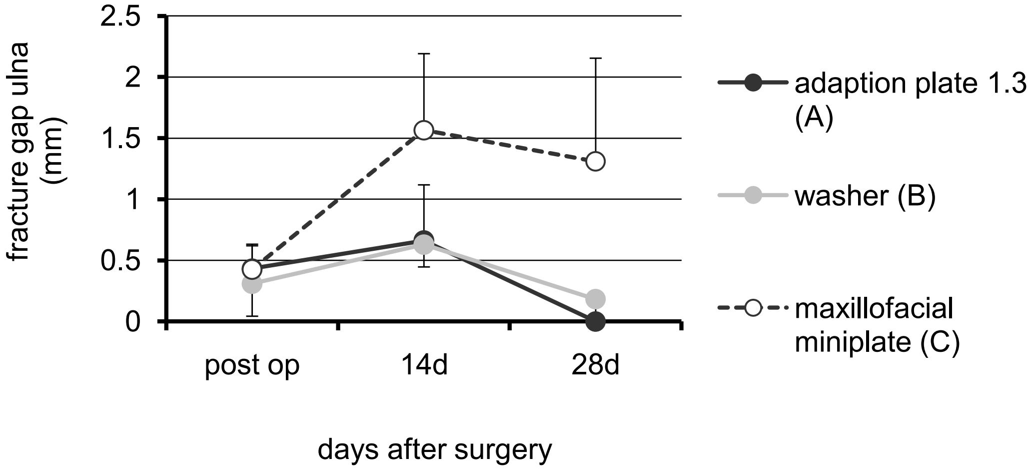

Fig. 41: The mean fracture gap at the caudal site of the ulna and its standard deviation in the groups A, B and C measured immediately after surgery as well as two and four weeks later.

6.5.7 **Cortex diameter**

Mean bone width of all pigeons of group A, B and C 14 days after the surgery proximal to the fracture site was 0.48 mm (± 0.06 mm) (see appendix).

6.5.8 **Statistical analysis of callus formation**

Statistics: ANOVA did not reveal any significant difference in callus width or the callus/bone ratio between the groups. Mean callus including the ulna after 14 days in group A was 8.7 mm (±1.0 mm), in group B 9.1 mm (±2.1 mm) and in group C 7.5 mm (±0.7 mm). After 28 days mean callus in group A was 8.5 mm (±1.3 mm), in group B 9.3 mm (± 0.9 mm) and in group C 8.3 (±1.2 mm).

6.5.9 **Subjective impression of the fixated wing and the fracture**

6.5.9.1 Preliminary study

The subjective impression of the two pigeons of the preliminary study was good immediately after surgery as well as 28 days after surgery (Appendix IIa, IVa).

6.5.9.2 Adaption plate 1.3, group A

Of group A, the postoperative impression was good in all pigeons except in one animal (16.7%) where it was judged moderate because the fracture was not completely reduced. One day after surgery one pigeon had to be euthanized because of a loose implant and an instable fracture supposedly after excessive wing flapping. Fourteen days after surgery fracture healing of 40% of the pigeons of group A was classified as good, 40% as moderate in one pigeon because of an additional fracture and in another because of retracted screws. In one pigeon fracture healing was even classified as poor because of osteomyelitis and an additional fracture. Twenty-eight days after surgery fracture healing of 100% of the remaining pigeons of group A was classified as good. The osteomyelitis had resolved without therapy. (Appendix IIa, IIIa, IVa).

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6.5.9.3 Washer, group B

The postoperative impression was good in all of the pigeons. Two pigeons had to be euthanized two and three days after surgery supposedly because of excessive wing flapping. Fourteen days after surgery fracture healing was considered good in 50% of the pigeons. In one pigeon (25%) fracture healing was moderate because of loosening of screws and even loss of one screw. In the fourth remaining pigeon of group B fracture healing was classified as poor because of osteomyelitis. Twenty-eight days after surgery fracture healing was good in 75% of the pigeons and poor in the one pigeon with osteomyelitis (25%) (Appendix IIb, IIIb, IVb).

6.5.9.4 Maxillofacial miniplate, group C

The postoperative impression was good in all (100%) of the pigeons. It was moderate 14 and 28 days after surgery because of plate bending and twisting resulting in a malaligned position (Appendix IIc, IIIc, IVc).

6.6 Post mortem evaluation

There was no case of synostosis between radius and ulna in any plate system.

6.6.1 Preliminary study

Both implants of this group were intact, and removable callus formation was 9.9 mm and 7.04 mm in dorsoventral direction, and 8.9 mm and 6.8 mm in laterolateral direction (Appendix V)

6.6.2 Adaption plate 1.3, group A

There was no case of plate distortion, bending or twisting in all five remaining pigeons. In one pigeon that flapped with the wings after awakening from anaesthesia, the two screws of the distal fragment were torn out. From the distal part of the ulna a fragment seemed to have come off and adhered to the bone again.
In another pigeon the proximal end of the plate protruded one millimetre through the skin. The implant was removable in two of five cases. In one case only the screws could be removed (Fig. 42 and 43) while in two of five cases the plate was overgrown with callus which made plate removal difficult. Ulna and radius were stable in all pigeons of this group. In the pigeon with the screw-loosening, the affected two screw holes were enlarged and filled with brown, friable material indicating osteomyelitis. Mean callus formation of the ulna in dorsoventral direction was 8.7 mm (± 1.4 mm) and 8.3 mm (1.1 mm) in laterolateral direction (Appendix V).

Fig. 42: Dorsal view on radius and ulna four weeks after fracture fixation with an adaption plate 1.3. The screws were removed. Callus formation is visible in both bones.

Fig. 43: Lateral view of an ulna of a pigeon four weeks after fixation with an adaption plate 1.3. The plate is overgrown with callus. Only the screws were removable

6.6.3 Adaption plate 1.3 with washers, group B

No case of plate deformation occurred. In one case of the four remaining pigeons, a proximal screw was missing, but the washer was still present on the bone and a screw in the distal fragment was loose. In another pigeon of this group, the plate was protruding through the skin, only the most distal screw was positioned in the bone, and the other screws and the washers of the two proximal screws were missing. They were most probably lost through the skin suture. The protruding of this plate was not noticed until euthanasia. The implants of the other two pigeons of this group were in position. The plate was removable (Fig. 45) in all four cases of this group, but in one case plate removal was very difficult. The fragments of the ulna of the pigeon with the protruding plate were only connected with connective tissue. This ulna was not stable and in the radius a fistula was present. All other pigeons had formed stable callus four weeks after surgery (Fig. 44). In the pigeon with the missing screw, the callus was additionally enlarged proximally to the former cutting site. Mean callus formation of the ulna in dorsoventral direction was 8.5 mm (± 1.3 mm) and 8.3 mm (± 1.2 mm) in laterolateral direction (Appendix V).

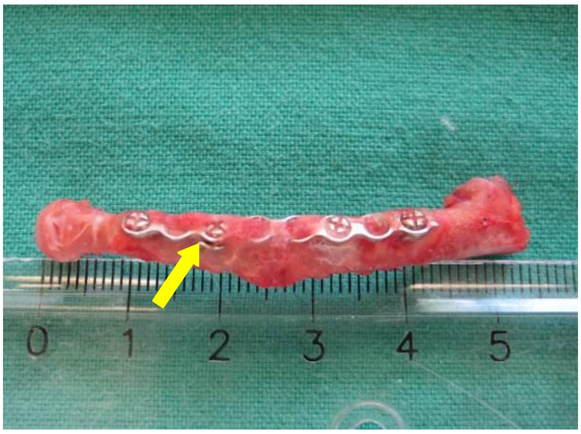

Fig. 44: Ulna with stable callus four weeks after fracture fixation with an adaption plate 1.3 with washers. The arrow is indicating a washer.

Fig. 45: Ulna four weeks after fracture fixation with an adaption plate 1.3 with washers. The plate was removed and the washers are visible above the screwholes.

6.6.4 **Maxillofacial miniplate, group C**

In all pigeons of the maxillofacial group the plate was bent (Fig. 46) and twisted (Fig. 47). The fragment ends were fused in a more acute angle. The plate was not removable because the plate was overgrown with callus in all cases. In one pigeon there was a small fistula in the callus of the ulna and brown and friable material was present at the cutting site of the radius indicating osteomyelitis. In another pigeon a small hole cranial of the cutting site was present. The wing was stable in all pigeons of this group. Mean callus formation of the ulna in dorsoventral direction was 8.1 mm (± 1.3 mm) and 7.3 mm (± 0.8 mm) in laterolateral direction (Appendix V).

Fig. 46: Dorsal view on radius and ulna four weeks after fracture fixation with a maxillofacial miniplate, Compact 1.0. The plate is overgrown with callus. The fragment ends of the ulna were fused in a more acute angle and the plate was bent.

Fig. 47: Ventral view of an ulna four weeks after fracture fixation with a maxillofacial miniplate. The screw ends are pointing in different directions indicating torsion of the plate.

In Tab. 7 the most important findings and differences between the groups are summarized.

Tab. 7: Findings regarding bone plates used in pigeons to treat ulna fractures

	Adaption plate 1.3 group A	**Adaption plate 1.3 with washers group B**	**Maxillofacial miniplate group C**
Plate twisting and bending	0 of 5 pigeons (0%)	0 of 4 pigeons (0%)	6 of 6 pigeons (100%)
Osteomyelitis	1 of 5 pigeons (20%)	1 of 4 pigeons (25%)	2 of 6 pigeons (33%)
Good flight ability	5 of 5 pigeons (100%)	2 of 4 pigeons (50%)	0 of 6 pigeons (0%)
Detachment of the plate (pigeons included which were euthanized earlier because of excessive wing flapping)	2 of 6 pigeons (33%)	4 of 6 pigeons (67%)	0 of 6 pigeons (0%)

7 Discussion

Critic of the study:

A major disadvantage of the study was that the sequence of the surgeries was not randomized. The surgeries were started with group A (Adaption plate 1.3), continued with group B (Adaption plate 1.3 with washers), and finally the surgeries of group C (maxillofacial miniplates) were performed. This order was chosen because of the availability of the osteosynthesis equipment. In the beginning of the experimental period more complications occurred than at the end, which emphasizes the importance of a period of practicing prior to the experimental surgeries, and a randomisation of the sequence in which animals of the different treatment groups are subjected to surgery. With this sequence of the surgeries the first group (group A, adaption plate 1.3) had the most disadvantages. Nevertheless the most promising results were achieved with group A. With a randomisation this group might have achieved even better results. Some cases with excessive wing flapping with subsequent loosening of the screws leading to repair failure could probably have been prevented with a bandage. However, to prevent shortening of the propatagium the bandage has to be removed after a short time or physical therapy is necessary.

7.1.1 Preliminary study

The surgeries and the fracture healing of the two pigeons from the preliminary study with the adaption plate 1.3 were uneventful. No loosening of screws was noted, therefore the surgical procedure including the chosen drill bit was considered to be adequate. The results of these two pigeons confirm the conclusion that treatment A was relatively successful in this study.

7.1.2 Adaption plate 1.3, group A

In five of six pigeons (83%) of group A, the fracture was healed after 28 days and the birds had no problems to fly from the ground to the roosting bar at a height of 130 - 150 cm. One pigeon had to be euthanized one day after the surgery because of tearing out of the plate during excessive flapping. The stainless steel plate appears to be strong enough to withstand the forces of the wing, and the size was adequate for the ulna of pigeons. The used plate is smaller than the 2.8 cm x 5 mm plate with

1.5 mm bone screws Yamazoe et al. (1994) used in humeral fractures of pigeons, and therefore it has potential to be used in smaller species.

Stainless steel is considered less inert than titanium to tissue reaction (Steinemann 2002). However, in the present study no increased foreign body reaction was noticed macroscopically stainless steel implants compared to the titanium implants. One problem was that immediately after surgery only 50% of the screws were bicortical. Because bicortical screws have a much higher pullout strength than screws that were placed only through one cortex (Heller et al. 1996), the screws should always be placed bicortical. This could have been achieved with longer screws. Another element that might have accounted for loosening and tearing out of the screws is the anatomy of avian bone. Studies of Asnis et al. (1996) and revealed that the holding power of bone screws depends most importantly upon the bone material density. Seller et al. (2007) found that screw design had no significant influence in vertebral body screws, but outer diameter of the screw, screw length and bone mineral density (BMD). In spite of comparisons of literature data on BMD of mammals and birds (Tab. 5. and 6.), it remains unclear whether birds have higher BMD compared to mammals. BMD measurements are highly dependent on the measured bone region, age, sex and feeding of the animals and are therefore difficult to compare.

Other screws with larger outer diameter could not be applied in this study, due to the entire diameter of the pigeon ulna. Asnis et al (1996) also found that in screw design, the outer diameter of a cancellous bone screw thread was most important for holding strength; additionally the number of threads and the root diameter was important. The thread pitch of the screws used in group A with the adaption plate 1.3 was 0.5mm and the mean cortical diameter proximal to the fracture site was only 0.48 mm (± 0.06 mm). Werthern and Bernasconi (2000) state that the bone thickness should be twice the thread pitch distance of the screw to create adequate compression. The disproportion between thread pitch and cortical thickness might have contributed to the loosening of the screws and tearing out of the plate in the pigeon that was euthanized one day after surgery. Birds have thinner cortices compared to terrestrial mammals (Swartz et al. 1992), which might cause this disproportion between thread pitch and cortex thickness. In pneumatised bones, cortical thickness is even lower than in marrow-filled bones (Casinos and Cubo 2001), which could cause additional difficulties for osteosynthesis in pneumatised bones e.g. humeral fractures. In Fig. 48 and Fig. 49, the 1.3 stainless steel screw used in group A and B and the 1.0 titanium screw used in group C are compared. The thread pitch is twice as high in the 1.3 stainless steel screw compared to the 1.0 titanium screw.

Fig. 48: A 6 mm long 1.3 stainless steel screw (Synthes GmbH, Oberdorf, Switzerland) with a thread pitch of 0.5 mm used in group A and B. The thread pitch is twice as high as in the 6 mm long 1.0 titanium screw of group C (Fig. 48)

Fig. 49: A 6 mm long 1.0 titanium screw of group C (Synthes GmbH, Oberdorf, Switzerland) with a thread pitch of 0.25 mm.

When using screws in thinner cortices, the reduction of threads engaged in the cortex leads to a progressive loss of stability. However, a smaller screw, even with relatively more engaged threads, will have a lower absolute holding strength (Seebeck et al. 2000). Improvement in screw holding power could possibly also be achieved with a smaller drill hole.

The stainless steel plate of these systems appears to meet the requirements of avian surgery, but even with very careful handling it will never be possible to prevent wing flapping completely, especially in wild birds. Improvement may possibly be achieved by using the stainless steel adaption plate 1.3 in combination with more and longer screws (7 or 8 mm long) and preferably also screws with a smaller thread pitch (e.g. 0.25 mm). The use of a smaller drill bit might also be beneficial (e.g. a 0.9 mm drill). In spite of requests for such screws at several medical instrument suppliers they were not available to the author.

7.1.3 Adaption plate 1.3 with washers, group B

The application of the washers did not increase the subjective difficulty of the surgery markedly. Also mean surgical time of group B was not significantly longer than in group A and even shorter than in group C. But with this plate system, 2 of 6 Pigeons (33.3%) were euthanized one and two days after the surgery, because of a loose plate supposedly after excessive wing flapping. Additionally, only in 25% of the pigeons all screws were bicortical immediately after surgery. Fourteen and 28 days postoperative there was no pigeon with all screws bicortical, which is associated with a much lower screw holding power (Heller et al. 1996). The author suspects that the increased tearing out of screws was due to inadequate screw length. The screw length was the same as in the system with the adaption plate 1.3, although the washer between the plate and the bone was 0.7 mm thick. In addition, the size of avian cortices may also play an important role in screw holding power as mentioned above. Unfortunately, the insufficient holding power of the screws was not noticed during practicing the method on dead pigeons. The plate remained unchanged in all pigeons. This supports the results of group A, that the stainless steel plate itself is strong enough to withstand the forces of the wing.

The intention of this system was to reduce the compression of the periostum and the vascular damage the plate causes to the bone as described by Jörger (1987), Perren et al. (1990) and Tepic et al. (1992). This was achieved by placing washers between the bone and the plate. Similar to the Schuhli nuts described by Kolodziej et al. (1998), these washers elevate the plate from the bone and thus minimize contact to the bone. However, there was no apparent effect of reduced plate contact to the bone healing at necropsy. The callus had grown over the plate after 28 days. Probably thicker washers than the used 0.7 mm could be used to increase the space between bone and the plate. Additionally nuts with a thread could be used to provide angular stability, similar to the locking mechanism of internal fixators (El-Sayed et al. 2001; Kolodziej et al. 1998). However larger nuts with a thread could eventually cause difficulties in wound closure above the implant.

7.1.4 **Maxillofacial miniplate plate, group C**

The wing skeleton is subjected to considerable torsional loading during flight (de Margerie 2002). Similar to the previous study of Christen et al (2005), the titanium miniplates were unable to provide enough stability to withstand these forces. All of the implants were bent, twisted, and in one pigeon the plate was fractured, even though longer plates were used than in the study of Christen et al. (2005), as recommended by these authors and by Howard (1990). The maxillofacial miniplates are very malleable and easy to adapt, but not designed for the repair of bones loaded under torsion. They are intended for human maxillofacial fractures, where only minimal mechanical stress is present (Christen et al. 2005). Presumably the malposition of the fracture fragments in a smaller angle caused by the bent plates is responsible for the poor flight ability of this group. To prevent fatigue fracture Katakure at al. (2004) recommend to use high-strength titanium alloy instead of pure titanium. There is also less movement in a load versus deformation test in stainless steel plates compared to titanium plates of the same dimensions (Coughlan and Miller 1998). But even though titanium alloy plates and screws are widely used in human orthopaedics, they are only marginally better, yet significantly more expensive than stainless steel implants, and therefore not frequently used in veterinary orthopedics (Coughlan and Miller 1998).

All screws remained bicortical in 100% of the pigeons until 28 days after surgery. No case of loosening or tearing out of the plate occurred in spite of plate bending and twisting. The screws had the same length as the screws used with the adaption plate 1.3 with and without washers. Therefore the author suspects, that the better holding power compared to the other screws is explained by the smaller thread pitch. The thread pitch is only 0.25 mm which allows compression in even 0.5 mm thick bones (von Werthern and Bernasconi 2000). The mean cortical diameter of the ulna proximal to the fracture site was only 0.48 mm (± 0.06 mm), nevertheless this seems enough to provide sufficient holding power for the screws. The good holding power of these screws might also be due to the smaller leverage to the screws if the plate yields to stress. Another reason could have been the relatively smaller drill hole. With the screws of the maxillofacial miniplate a 0.70 mm drill from the hardware store was used instead of the recommended 0.76 mm drill bit, because during practice of the surgery on dead pigeons the screws seemed too loose with the provided drill bit.

7.1.5 General requirements for bone plates in avian osteosynthesis

The requirements for plate systems for avian osteosynthesis are similar to other fixation techniques. The surgery has to be technically feasible. For some cases the collaboration of a bird specialist with a surgeon is necessary, because a certain level of skill is essential for plate application. The screws must be small enough to allow drilling of the holes without shattering of the bone. Postoperative handling e.g. treatment with analgesics must be possible, therefore the plates must be stable and the screws should remain bicortical and not become loose. Additionally the price of bone plates must be affordable for the average owner of a pet bird to become a part of daily routine in avian surgery. A 1.3 adaption plate with four screws costs approximately 245 CHF (Synthes GmbH, Oberdorf, Switzerland), a maxillofacial miniplate Compact 1.0 with four screws costs 370 CHF (Synthes GmbH, Oberdorf, Switzerland) while a FESSA external fixator system of 100mm length and 8mm diameter with 4 positive threaded pins costs about 100 Fr (Medical Solution GmbH, Hünenberg, Switzerland). This makes the plates still more expensive than external fixators, but especially the stainless steel plates are in an affordable range.

7.1.6 Applicability of the plate systems

In conclusion the adaption plate 1.3 seems to provide enough strength for osteosynthesis in a bird of the size of a pigeon. Likewise the screws of the maxillofacial miniplate seem to hold the implant well, although the maxillofacial miniplate bent in all cases. A combination of these two systems would therefore be beneficial; however, the heads of the maxillofacial screws are too small for the large holes of the adaption plate 1.3. For future trials the adaption plate 1.3 could be used either with other screws with a small thread pitch or the screws of the maxillofacial miniplate with a washer that prevents the screws from parting through the large holes of the adaption plate 1.3. To use the adaption plate 1.3 with the compatible screws but a smaller drill bit would be the easiest and probably most effective trial. To prevent the bird from flapping during the period immediately after surgery additional measures, like taping the wing tips together as suggested by Howard (1990), could be taken. Also a figure-of-8-bandage could be applied for the first days after surgery which would at the same time act as wound coverage and prevent contamination. However, Redig et al. (2001) describe a contraction of the patagium after three weeks of immobilisation therefore the bandage has to be removed soon enough. Additionally dermatitis, swelling of the surrounding soft tissue are described as complications of bandages (Weinstein and Ralphs 2004).

7.1.7 Indications for bone plates in birds

Because of its size, the adaption plate 1.3 could be applied to birds of similar size or slightly larger than pigeons e.g. falcons, African grey parrots (*Psittacus erithacus*) or amazon parrots (*Amazona* spp.). The technique clearly requires further modifications until it is applicable in daily routine. But it has several advantages compared to the use of external fixators and could for some indications achieve better healing results, e.g. plates provide rigid stability which leads to less callus formation than other fixation systems. Although primary fracture healing without callus formation is no longer recognized as desirable, because callus helps to secure the fracture (Schütz and Südkamp 2003), excessive callus formation can impair normal function. Therefore small callus formation is peculiarly important in fractures of the radius and ulna, because large callus formation can lead to a fusion of these bones. In wild birds intended for release, the fused radius and ulna prevent exact flight maneuvres, which are necessary e.g. for hunting. For this reason inadequate methods for fracture fixation may jeopardize the success of rehabilitation. Similar to the use in small animal surgery, plates should also be used for articular fractures, fractures that require compression e.g. non-union fractures, and to buttress non-reconstructable fractures and for arthrodesis.

Another indication for bone plates are very fractious or wild birds such as hawks. Plates may be indicated, because these birds may get caught in their external fixator or traumatise themselves when agitated. In cage birds that should be disturbed as little as possible, e.g. because they are breeding, bone plates may also be used rather than other fixation methods that require more frequent control. In this case it is possible not to remove the plate. Generally it is recommended to remove the plate to prevent painful cold transduction as described in mammals (Bennett and Kuzma 1992); in birds that are housed inside this is not important. Additionally in small animal surgery implant removal is not considered obligatory anymore, although it may be beneficial to prevent the bone from disuse atrophy (Coughlan and Miller 1998). However Glennon et al. (1994) and Muir et al. (1995) suggest not to remove the plate, because of no significant correlation between the change in cortical density between the plated limb and the contralateral limb. In this study in some cases the plate was already overgrown with callus after the periode of 28 days. Plate removal was even very difficult postmortally and in some pigeons impossible. For this reason the author suggests to remove the plates earlier. However Howard (1990) removed a bone plate after 7 weeks in a chronic malunited wing fracture; additionally Yamazoe (1994) remarked that healing in pneumatised bones lasts longer than in marrow filled bones. This indicates that the point of time when the plate is removed depends heavily on the location of the fracture, the kind of fracture and the healing process.

7.1.8 The tension side of the ulna

To absorb the tensile stress that could separate a fracture, bone plates should be applied to the tension surface of bones. In general the compression occurs on the concave surface of the bone and the tension on the convex surface of the bone (Johnson 2007). To the knowledge of the author, the tension site of the avian ulna has not yet been determined. Nickel et al. (2004a) state that the convex area of the ulna is located at the ventral site of the bone if the wing is adjacent to the body. Therefore this site should be considered to be the tension site. In the present study the plates were applied to the muscle free caudodorsal area because of the easier surgical access. The chosen plate location may have contributed to the bent implants of group C with the weak titanium maxillofacial miniplates. But a ventral access would have interfered with the insertion of the secondary remiges. The follicles of the secondary remiges must not be damaged because this may lead to malformation of the feathers. Since it is not feasible to place the plate at the tension side of the ulna, the stability of the plate is even more important

8 Conclusions

8.1.1.1 Conclusions based on the literature review

- There are no indications that birds have higher bone mineral or bone calcium levels than mammals.
- The ratio between cortex and medulla in avian forelimb bones is smaller than in mammalian bones to minimize torsional stresses occurring during flight.
- For several indications (articular fractures, fractious birds) bone plates have advantages over other fixations methods e.g. external fixators.
- The tension surface of the ulna is located at the ventral site of the bone if the wing is adjacent to the body. Because the secondary remiges insert at this location, plate application at the tension site of the ulna is not feasible, therefore the stability of the plate is very important.

8.1.1.2 Conclusions based on the experimental study

- The healing results as well as the flight performance of group A with the adaption plate 1.3 were good. Further improvement of the healing process may be achieved with additional measures (e.g. Figure-of-eight bandage combined with physical therapy).
- The washers used in group B were too thin to create a limited contact effect.
- The titanium maxillofacial miniplate, Compact 1.0 is too weak for avian surgery at the wings.

8.1.1.3 Conclusions based on practical experiences during the study

- It seems that in avian surgery screws with a smaller thread pitch or a smaller drill bit are necessary, because of the thinner cortices of avian bones. To prove this hypothesis a further trial is necessary.

9 Appendix

Appendix I: Overview over anaesthesia duration, surgical time, surgery and postsurgical period for the individual pigeons

Pigeon No	Treatment group	Implant	Anaesthesia duration (min)	Surgical time (min)
19A	preliminary study	Adaption plate 1.3	72	32
4A	preliminary study	Adaption plate 1.3	90	45
1B	A	adaption plate 1.3	70	40
2B	A	adaption plate 1.3	46	36
22B	A	adaption plate 1.3	55	36
23B	A	adaption plate 1.3	62	41
12B	A	adaption plate 1.3	45	30
14B	A	adaption plate 1.3	55	37
5B	B	washer	50	35
20B	B	washer	55	40
21B	B	washer	55	39
7B	B	washer	55	40
13B	B	washer	60	39
17B	B	washer	50	38
4B	C	Maxillofacial miniplate	55	35
6B	C	Maxillofacial miniplate	55	Not measured
8B	C	Maxillofacial miniplate	75	55
9B	C	Maxillofacial miniplate	55	40
16B	C	Maxillofacial miniplate	58	33
18B	C	Maxillofacial miniplate	55	35

Continuation of Appendix I: Overview over anaesthesia duration, surgical time, surgery and postsurgical period for the individual pigeons

Pigeon No	Surgery	Postsurgical period
19A	uneventful	uneventful
4A	uneventful	uneventul
1B	uneventful	flapping after awaking from anaesthesia, no palpable damage of the fracture fixation
2B	soft tissue trauma with the oscillating bone saw 1 screw placed oblequely	uneventful
22B	screw on the wrong place	uneventful
23B	uneventful	uneventful
12B	most distal screw slightly loose	excessive wing flapping 1 day after surgery, euthanasia
14B	difficulties to put in the most proximal screw, additional hole drilled more distally	uneventful
5B	uneventful	uneventful
20B	uneventful	excessive wing flapping 3 days after surgery, euthanasia
21B	uneventful	uneventful
7B	uneventful	excessive wing flapping 2 days after surgery, euthanasia
13B	uneventful	uneventful
17B	uneventful	uneventful
4B	uneventful	uneventful
6B	uneventful	uneventful
8B	difficulties to put in most distal screw	uneventful
9B	uneventful	uneventful
16B	uneventful	uneventful
18B	uneventful	uneventful

Appendix IIa: Radiological findings preoperative and immediately after surgery of the individual pigeons with adaption plates 1.3 from the preliminary study and group A

pigeon No	**4A**	**19A**	**1B**	**2B**	**22B**	**23B**	**12B**	**14B**
treatment group	preliminary study	preliminary study	A	A	A	A	A	A
implant	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3
preoperative	NAD	NAD	NAD	NAD	NAD	NAD	NAD	NAD
implant postoperative	screws bicortical	screws bicortical	screws bicortical	second proximal screw oblique and not bicortical	screw accidentally in the wrong screw hole	all screws bicortical	2 distal screws not bicortical	malpositioned screw, most distal and most proximal screw not bicortical
post op alignment of the fracture ends of the ulna	cortices aligned	cortices aligned	greater than 50%	cortices aligned	cortices aligned	greater than 50%	cortices aligned	less than 50%
post op alignment of the fracture ends of the radius	none	none	none	greater than 50%	aligned	less than 50%	none	less than 50%
overriding (mm)	-1.01	-0.9	- 1.9	none	none	none	-0.6	none
angle ulna postoperative (degree)	159.32	156	159	158	161	165	165	159
fracture gap postoperative (mm)	0.71	0.62	0.3	0.7	0.25	0.67	0.36	0.32
subjective impression	normal post op	normal post op	normal post op	normal post op	normal post op (screw in the wrong hole)	normal post op	normal post op	normal post op

Appendix IIb: Radiological findings preoperative and immediately after surgery of the individual pigeons from group B / washers

pigeon No	**5B**	**20B**	**21B**	**7B**	**13B**	**17B**
treatment group	B	B	B	B	B	B
implant	washer	washer	washer	washer	washer	washer
preoperative	NAD	NAD	NAD	NAD	NAD	NAD
implant postoperative	most proximal and most distal screw not bicortical	proximal screw not bicortical	all screws bicortical	most proximal screw not	all screws bicortical	most proximal screw not bicortical
post op alignment of the fracture ends of the ulna	greater than 50%	greater than 50%	aligned	greater than 50%	greater than 50%	aligned
post op alignment of the fracture ends of the radius	greater than 50%	greater than 50%	greater than 50%	greater than 50%	none	greater than 50%
overriding (mm)	none	none	none	none	-0.6	none
angle ulna postoperative (degree)	167	163	161	162	162	160
fracture gap postoperative (mm)	no gap	no gap, near perfect closure	0.3	0.4	0.5	0.65
subjective impression	normal post op	normal post op	normal post op	normal post op	normal post op	normal post op

Appendix IIc: Radiological findings before surgery and immediately after surgery of the individual pigeons from group C / maxillofacial miniplate

pigeon No	4B	6B	8B	9B	16B	18B
treatment group	C	C	C	C	C	C
implant	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate
preoperative	NAD	NAD	NAD	NAD	NAD	NAD
implant postoperative	alls screws bicortical	all screws bicortical	all screws bicortical	all screws bicortical	all screws bicortical	all screws bicortical
post op alignment of the fracture ends of the ulna	aligned	aligned	aligned	aligned	greater than 50%	greater than 50%
post op alignment of the fracture ends of the radius	none	greater than 50%	greater than 50%	less than 50%	less than 50%	less than 50%
overriding radius (mm)	-1.0	none	none	none	none	none
angle ulna postoperative (degree)	162	159	159	162	161	157
fracture gap postoperative (mm)	0.46	0.6	0.28	0.25	0.26	0.7
subjective impression	normal post op	normal post op	normal post op	normal post op	normal post op	normal post op

Appendix IId: Radiological findings of the pigeons that were euthanized one to three days after surgery because of implant failure

pigeon No	**12B**	**20B**	**7B**
treatment group	A	B	B
implant	adaption plate 1.3	washer	washer
No of days euthanized after surgery	1 day	3 days	2 days
implant after euthanization	none of the screws bicortical, prox. screw completely out of the bone	all screws retracted, proximal 3 screws completely out of the bone, most proximal washer missing	two proximal screws came out of the bone, most proximal screw lost
alignment of the fracture ends of the ulna	unreduced, overriding	unreduced, overriding	unreduced, overriding
subjective impression	repair failure	repair failure	repair failure

Appendix IIIa: Radiological findings of the individual pigeons with adaption plates 1.3 / group A, 14 days after surgery

pigeon No	1B	2B	22B	23B	14B
treatment group	A	A	A	A	A
implant	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3
implant day 14	implant ok	static	2 proximal screws loose, only partial in the cortex, bone has moved from the plate	implant ok	central segmental fracture from the proximal ulnar portion, loosening of all screws, retraction of the two distal screws, mottled opacity of the medullar cavity of the bone, indistinct periosteal and endosteal surfaces
alignment of fracture ends of the ulna, day 14	less than 50%	greater than 50%	aligned	greater than 50%	osteotomy fracture aligned, but new fracture of proximal bone
alignment of fracture ends of the radius, day 14	none	separated, 3mm	greater than 50%	none	none
overriding radius day 14 (mm)	-3	none	none	-0.67	none
angle ulna day 14(degree)	159	165	161	160	164 (plate and fracture fragment smaller angle)
fracture gap day 14 (mm)	no clear fracture gap because of the additional fracture	0.4	0.67	0.28	1.3mm, irregular fracture margins
other findings day 14	fracture of the distal ulna	-	-	-	osteomyelitis
width of mineralised callus day 14 (mm)	1.01	1.66	1.8	0.94	1.4
Cortex diameter day 14 (mm)	0.6	0.48	0.5	0.44	0.5
Callus formation score, day 14	1.6	3.53	3.6	2.14	2.8
subjective impression	complicated fracture, delaed callus formation	normal healing	healing bone, failing implant	normal healing	repair failure, osteomyelitis

Appendix IIIb: Radiological findings of the individual pigeons with washers / group B, 14 days after surgery

pigeon No	5B	21B	13B	17B
treatment group	B	B	B	B
implant	washer	washer	washer	washer
implant day 14	two distal screws not bicortical	slight retraction of the third screw	Most proximal screw lost, second and third proximal screw loosened and retracted	proximal two screws out of the bone
alignment of fracture ends of the ulna, day 14	greater than 50%	greater than 50%	greater than 50%	greater than 50%
alignment of fracture ends of the radius, day 14	none	none	less than 50%	separated no alignment
overriding radius day 14 (mm)	- 2.2	separated and overriding	none	none
angle ulna day 14 (degree)	163	158	160	155
fracture gap day 14 (mm)	0.57	0.55	0.5	0.9
other findings day 14	-	-	-	irregular raised periosteal reaction, lucency around the screws
width of mineralised callus day 14 (mm)	1.6	2.57	0.15	0.13
Cortex diameter day 14 (mm)	0.43	0.42	0.42	0.44
Callus formation score, day 14	3.72	6.12	0.36	0.30
subjective impression	healing fracture	normal healing	implant failure	implant failure, osteomyelitis

Appendix IIIc: Radiological findings of the individual pigeons with maxillofacial miniplates / group C, 14 days after surgery

pigeon No	**4B**	**6B**	**8B**	**9B**	**16B**	**18B**
treatment group	C	C	C	C	C	C
implant	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate
implant day 14	bicortical screws, implant rotated, bent	bicortical screws, implant rotated, bent	bicortical screws, implant rotated, bent	bicortical screws, implant bent and rotated	bicortical screws, implant bent and rotated	bicortical screws, implant bent and rotated
alignment of fracture ends of the ulna, day 14	greater than 50%	greater than 50%	greater than 50%	greater than 50%	greater than 50%	greater than 50%
alignment of fracture ends of the radius, day 14	none	none	none	none	none	none
overriding radius day 14 (mm)	-0.14	-4.25	-1.81	-3.31	-3.89	-2.06
angle ulna day 14 (degree)	131	127	138	141	127	141.5
fracture gap day 14 (mm)	1.17	2.02	1.62	0.65	2.43	1.5
other findings day 14	-	-	-	-	-	-
width of mineralised callus day 14 (mm)	no mineralized callus formation at the caudal aspect of the bone	2.29	1.22	1.1	no callus formation	1.5
Cortex diameter day 14 (mm)	0.58	0.48	0.56	0.44	0.41	0.45
Callus formation score, day 14	-	4.78	2.19	2.5	-	3.33
subjective impression	Implant failing, delayed callus formation	Implant failure, plate fractering 6th hole	Healing malaligned, callus faintly mineralised	healing but malaligned from implant rotation and bending	delayed healing, bending and rotation of the implant	healing but malangled ulna, healing but overriding radius

Appendix IVa:: Radiological findings of the individual pigeons with adaption plates 1.3 from the preliminary study and group A, 28 days after surgery

Pigeon No	4A	19A	1B	2B	22B	23B	14B
treatment group	preliminary study	preliminary study	A	A	A	A	A
implant	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3	adaption plate 1.3
implant day 28	both distal screw not bicortical	most distal screw not bicortical	Implant unchanged	Implant unchanged	Implant unchanged	implant unchanged	two proximal screws not bicortical
alignment of fracture ends of the ulna, day 28	greater than 50%	cortex aligned	less than 50%	greater than 50%	aligned	greater than 50%	just callus
alignment of fracture ends of the radius, day 28	none	none	none	none	aligned	none	none
overriding radius day 28 (mm)	-1.04	-0.48	-2.78	-1.4	none	0.46	-2.6
angle ulna day 28 (degree)	152	152	155	165	162	160	162
fracture gap day 28 (mm)	0.4	0.58	no fracture gap, callus	no fracture cap callus	no fracture gap, callus	no fracture gap, healed	everything incorporated in callus
other findings day 28	-	-	healing fracture	-	-	-	healed fracture, resolved osteomyelitis
width of mineralised callus day 28 (mm)	1.3	1.1	3.35	1.15	1.48	1.1	1.85
Cortex diameter day 28 (mm)	0.34	0.38	0.6	0.54	0.5	0.51	0.43
Callus formation score, day 28	3.82	2.9	5.5	2.12	2.96	2.16	4.3
subjective impression	normal healing	normal healing	progressive healing	normal healing	normal healing	normal healing	healed fracture, resolved osteomyelitis

Appendix IVb: Radiological findings of the individual pigeons with washers / group B, 28 days after surgery

Pigeon No	**5B**	**21B**	**13B**	**17B**
treatment group	B	B	B	B
implant	washer	washer	washer	washer
implant day 28	unchanged	unchanged	unchanged	progressive bone lysis, indadequate, incomple callus formation
alignment of fracture ends of the ulna, day 28	greater than 50%	callus	greater than 50%	less than 50%
alignment of fracture ends of the radius, day 28	none	none	less than 50%	less than 50%
overriding radius day 28 (mm)	-0.6	-1.5	none	none
angle ulna day 28 (degree)	163	160	159	156
fracture gap day 28 (mm)	no fracture gap, callus	no fracture gap, callus	0.49	0.24
other findings day 28	-	-	-	osteomyelitis, implant failure
width of mineralised callus day 28 (mm)	0.95	1.56	1.64	1.5
Cortex diameter day 28 (mm)	0.49	0.4	0.44	0.4
Callus formation score, day 28	1.94	3.9	3.7	3.75
subjective impression	healing fracture	normal bone healing	healing fracture	not healing, incomplete callus formation, delayed union

Appendix IVc: Radiological findings of the individual pigeons with maxillofacial miniplates / groupC, 28 days after surgery

Pigeon No	**4B**	**6B**	**8B**	**9B**	**16B**	**18B**
treatment group	C	C	C	C	C	C
implant	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate	maxillofacial miniplate
implant day 28	Implant unchanged	Implant failure, plate fracturing 6th hole	Implant unchanched	Implant unchanged	Implant unchanged	Implant unchanged, lucency around the plate
alignment of fracture ends of the ulna, day 28	greater than 50%	greater than 50%	greater than 50%	greater than 50%	greater than 50%	greater than 50%
alignment of fracture ends of the radius, day 28	none	none	none	none	none	none
overriding radius day 28 (mm)	-0.21	-3.75	-2.2	-3.57	-3.72	-2.22
angle ulna day 28 (degree)	135	133	140	143	126	141.88
fracture gap day 28 (mm)	0.79	0.68	1.15	0.7	2.84	1.7
other findings day 28	-	-	-	-	-	osteomyelitis
width of mineralised callus day 28 (mm)	1.15	1.48	cranial part 2.22; no callus on the caudal aspect of the ulna	0.16	0.9 (Callus larger medially)	1.1
Cortex diameter day 28 (mm)	0.59	0.53	0.53	0.72	0.44	0.49
Callus formation score, day 28	1.95	2.79	-	0.22	2	2.24
subjective impression	healing fracture, bridging callus, malunion	bridging callus, healing fracture malalignement	bridging callus in the fracture gap, callus greater on the cranial side of the ulna	healed malangled, malaligned	hiling malaligned	osteomyelitis callus formation but incomplete bridge

Appendix V: overview post-mortem examination for the individual pigeons

Pigeon No	Treatment group	Implant	Euthanasia
19A	preliminary study	Adaption plate 1.3	
4A	preliminary study	Adaption plate 1.3	
1B	A	adaption plate 1.3	
2B	A	adaption plate 1.3	
22B	A	adaption plate 1.3	
23B	A	adaption plate 1.3	
12B	A	adaption plate 1.3	1d post op, excessive flapping, tearing out of implant
14B	A	adaption plate 1.3	
5B	B	washer	
20B	B	washer	3 d post op excessive flapping, tearing out of implant
21B	B	washer	
7B	B	washer	2 d post op excessive flapping, tearing out of implant
13B	B	washer	
17B	B	washer	
4B	C	Maxillofacial miniplate	
6B	C	Maxillofacial miniplate	
8B	C	Maxillofacial miniplate	
9B	C	Maxillofacial miniplate	
16B	C	Maxillofacial miniplate	
18B	C	Maxillofacial miniplate	

Continuation of Appendix V: overview post-mortem examination for the individual pigeons

Pigeon No	Condition of implant	Implant removable?	Bone	Stability
19A	intact	yes	NAD	stable
4A	intact	yes	NAD	stable
1B	2 distal screws torn out, distal part of the bone detached, bone chip at the distal part of the bone adhered to the bone	no	screw holes enlarged, filled with brown, friable material, indicating osteomyelitis	stable
2B	intact	no	NAD	stable
22B	intact	yes	NAD	stable
23B	intact	only the screws removable	NAD	stable
12B	-	-	-	-
14B	intact, proximal end of the plate protruding 1 mm through the skin	yes	proximal of the fracture as well callus formation	stable
5B	intact	yes, but only difficultly	NAD	stable
20B	-	-	-	-
21B	intact	yes	NAD	stable
7B	-	-	-	-
13B	second distal screw loose, proximal screw missing	yes	proximal of the fracture as well callus formation	stable
17B	plate protruding through the skin, only most distal screw still in the bone, the two proximal washers missing	yes	fracture fragments only connected with connective tissue; fistula in the radius	not stable
4B	bent, twisted	no	NAD	stable
6B	bent, twisted	no	small hole cranial to fracture site of the ulna	stable
8B	slightly bent, twisted	no	NAD	stable
9B	bent, twisted	no	NAD	stable
16B	bent, twisted	no	NAD	stable
18B	bent, twisted	no	small fistula in the callus of the ulna with brown, friable material at the cutting site of the radius indicating osteomyelitis.	stable

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